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Observation Computation Module (OCM)

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SHUTTLE PROGRAM

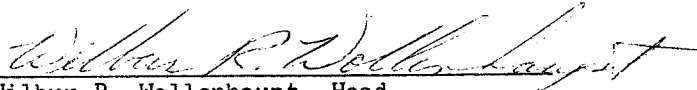
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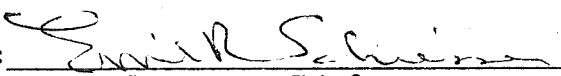
LEVEL C
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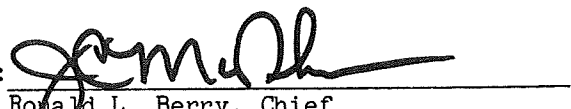
FORMULATION REQUIREMENTS
OBSERVATION COMPUTATION MODULE (OCM)

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PREFACE

The Mathematical Physics Branch/Mission Planning and Analysis Division has the responsibility to provide the functional ground navigation software formulation requirements for the Mission Control Center (MCC) low-speed processing phases during Operations Project Shuttle (OPS).

The ground navigation software formulation requirements are logically organized into volumes. This organization is presented in the accompanying table. The material in each volume presents the level C formulation requirements of the processors and modules required to process low-speed tracking data and perform orbit determination and other navigation related computations. Each volume describes the formulation requirements of the identified processor or module specified in the OPS MCC Ground Navigation Program Level B Software document (ref. 1). The inputs and outputs required to accomplish the functions described are specified.

OPS MCC GROUND NAVIGATION PROGRAM LEVEL C SOFTWARE REQUIREMENTS

ORBIT DETERMINATION PROCESSING FORMULATION DOCUMENT

Volume I	Introduction and Overview
Volume II	Low-Speed Input Processor (LSIP)
Volume III	Bias Correction Processor (BCP)
Volume IV	Data File Control Processor (DFCP)
Volume V	Orbit Determination Executive (ODE)
Volume VI	Convergence Processor (CP)
Volume VII	Differential Correction Module (DCM)
Volume VIII	Data Editing Processor (DEP)
Volume IX	Covariance Matrix Processor (CMP)
Volume X	State Transition Matrix Module (STMM)
Volume XI	Observation Computation Module (OCM)
Volume XII	Measurement Partial Derivative Module (MPM)
Volume XIII	Residual Computation Processor (RCP)
Volume XIV	Display Processor (DP)

78FM30:XI

VOLUME XI

OBSERVATION COMPUTATION MODULE (OCM)

CONTENTS

Section		Page
1.0	<u>CORRELATION TO LEVEL B</u>	1
2.0	<u>GENERAL DESCRIPTION</u>	1
3.0	<u>FORMULATION OF EACH FUNCTION</u>	2
3.1	<u>RANGE MEASUREMENT MODELS</u>	2
3.1.1	<u>Computation of Geometrical Signal Transit Time</u>	4
3.1.2	<u>Application of Refraction Correction</u>	4
3.1.3	<u>Relay Range Ambiguity Adjustment</u>	5
3.1.4	<u>Residual Computation</u>	6
3.2	<u>DOPPLER MEASUREMENT MODELS</u>	6
3.2.1	<u>Computation of Signal Delay Times at Start and End of Count Interval</u>	8
3.2.2	<u>Basic (Uncorrected) Differenced-Range Doppler Models</u>	8
3.2.3	<u>Application of Refraction and Bias Corrections</u>	9
3.2.4	<u>Residual Computation</u>	12
3.3	<u>ANGLE MEASUREMENT MODELS</u>	12
3.3.1	<u>A,E Angle Measurement Models</u>	13
3.3.2	<u>X_{N/S}, Y_{N/S} Angle Measurement Models</u>	15
3.3.3	<u>X_{E/W}, Y_{E/W} Angle Measurement Models</u>	16
3.4	<u>LIGHT TIME ALGORITHM</u>	17
3.4.1	<u>Receiver Position Computation</u>	20
3.4.2	<u>Computation of Signal Delay Times</u>	20
3.4.3	<u>Iterative Computation Procedure</u>	23
3.4.4	<u>Output from Light Time Algorithm</u>	26
3.5	<u>REFRACTION CORRECTION MODELS</u>	26
3.5.1	<u>Range Refraction Correction Model</u>	28
3.5.2	<u>Doppler Refraction Correction Model</u>	29
3.5.3	<u>Elevation Refraction Correction Model</u>	31
3.6	<u>M50 TO ENU-TOPODETTIC TRANSFORMATION</u>	32
4.0	<u>INPUTS TO OCM</u>	33
5.0	<u>OUTPUTS FROM OCM</u>	35

Section		Page
6.0	<u>CONSTRAINTS</u>	38
7.0	<u>SUPPLEMENTARY INFORMATION</u>	38
8.0	<u>REFERENCE</u>	38
9.0	<u>BIBLIOGRAPHY</u>	38
APPENDIX - FLOW CHARTS FOR OCM MECHANIZATION		A-1

TABLE

Table	Page
3.4.3-I COMPUTATION PROCEDURE	24

FIGURES

Figure		page
1	Direct data signal path configuration	39
2	Relayed data signal path configuration	39
3	Azimuth, elevation angles	40
4	$X_{N/S}$, $Y_{N/S}$ antenna angles	41
5	$X_{E/W}$, $Y_{E/W}$ antenna angles	42

1.0 CORRELATION TO LEVEL B

This document presents the level C software requirements that satisfy the level B software requirements specified for the observation computation module (OCM) in the following sections of JSC IN 77-FM-57 (ref. 1): sections 5.9, 6.0 (fig. 6-8), 7.2.8, and 8.3.8.

2.0 GENERAL DESCRIPTION

The navigation tracking data observations to be used in the Shuttle OPS ground navigation programs are derived from electromagnetic signals. An electromagnetic signal is sent from a ground transmitter to a spacecraft, either directly or via a relay satellite, where it is retransmitted and subsequently received at a ground receiving station. All observations (or measurements) are related to the characteristics of this received electromagnetic signal; i.e., the angle of the incoming signal, the ratio of the received to the transmitted frequency, or the round-trip signal transit time. The actual measurements of these quantities are referred to as the "observed" data.

The OCM is used to compute estimated, refraction corrected, data measurement values and to calculate tracking data residuals (observed values minus computed values) for use in the differential correction module (DCM) and the residual computation processor (RCP). All computed measurement values are based on a user-specified dynamic model and either a user-specified input vector or the current orbit determination solution vector. The measurement values are computed at times corresponding to the actual data measurement times at the ground receiving station.

The OCM is required to compute estimated measurement values for angular, range, and Doppler data. The angular data type includes angle pairs for three types of antenna mounts (azimuth/elevation; X/Y with the X-axis oriented east/west; and X/Y with the X-axis oriented north/south). The range data type includes radar bounce (skin track), C-band beacon, S-band sidetone (for direct tracking), and S-band or Ku-band PN ranging (for TDRS tracking data relay satellite relay tracking). The Doppler data types include S-band direct, and S-band and Ku-band relayed Doppler.

The first step in the measurement computation process is to use a light time algorithm to compute the times of signal transmission and the positions and velocities of the ground stations and spacecraft involved in the round-trip signal path. These computations are performed in the Aries mean-of-1950 (M50) Cartesian coordinate system.

The next step is to rotate the M50 receiving station vector to the topodetic coordinate system at the ground station and compute the angle measurements and refraction corrections. The range measurement, in terms of total round-trip signal-path length, is computed and corrected for refraction effects. Finally, the Doppler measurement is computed and corrected for refraction effects.

The residual is then calculated. If an angle residual is involved, a quadrant test is made and, if required, the computed measurement is adjusted to corre-

spond to the convention used for angular data measurements. If a range residual is involved, a test is made, and if required, corrections are applied to the computed measurement to resolve range ambiguity interval problems.

Each of the major functions of the OCM is described in section 3.0. The sequence of mathematical computations and overall logic flow for this module is presented in flow chart OCM of appendix A. The coordinate systems used in the OCM are defined in volume XIV of these requirements.

3.0 FORMULATION OF EACH FUNCTION

The general organization of these formulations is indicated by the headings of the major subsections as follows:

- 3.1 RANGE MEASUREMENT MODELS
- 3.2 DOPPLER MEASUREMENT MODELS
- 3.3 ANGLE MEASUREMENT MODELS
- 3.4 LIGHT TIME ALGORITHM
- 3.5 REFRACTION CORRECTION MODELS
- 3.6 M50 to ENU TOPODETTIC TRANSFORMATION

The first three subsections give the complete formulations for the models of the radar measurement types. These models make repeated use of a light time algorithm (formulated in section 3.4) and employ refraction correction models (formulated in section 3.5). In addition, sections 3.3 and 3.5 make repeated use of a transformation of station-centered relative vectors (in M50 coordinates) to ENU topodetic coordinates. This transformation is formulated in section 3.6.

3.1 RANGE MEASUREMENT MODELS

Two general forms of the range measurement model will be given:

Direct range measurement (IDOP = 0)

Direct range includes skin track ranging, C-band beacon ranging, and S-band sidetone ranging.

Relay range measurement (IDOP = 1)

Relay range (for TDRS relay tracking) includes S-band and Ku-band PN ranging for both two-way/three-way and hybrid-relay tracking configurations.

In both cases, the computed range is the total signal path distance, from transmitter to receiver, corrected for tropospheric refraction. In the case of relay range, this distance is computed modulo the ambiguity interval (PN code length) so as to make it comparable with the radar observation.

Signal-path configurations for direct range and relay range are shown in figures 1 and 2. A summary table that defines each of the participating points along the signal path and the point index notation convention is given in light time algorithm (sec. 3.4).

Input parameters required for the range measurement models are listed as follows:

IDOP = Flag that defines tracking configuration

0 = Direct tracking; 1 = Relay tracking

t_R = Range measurement time

G_{RNG} = Range observation

A_R = Range ambiguity interval (IDOP = 1 only)

Inputs required for light time algorithm:

These parameters are defined in detail in section 3.4. They are summarized for reference as follows:

$(\lambda_R, r_{GR}, Z_{GR}, \phi_{DR})$ = Receiver location parameters

$(\lambda_X, r_{GX}, Z_{GX}, \phi_{DX})$ = Transmitter location parameters

$\overline{EPH}(I)$ = Nine-point ephemeris tables ($I = 1, 2, 3$)

Inputs required for refraction correction model:

These parameters are defined in detail in section 3.5. They are summarized for reference as follows:

N_R = Refraction modulus at receiver

H_R = Scale height for receiver

N_X = Refraction modulus at transmitter

H_X = Scale height for transmitter

REFIND = Low-speed refraction correction indicator

Parameters obtained from system interfaces

C = Velocity of light

3.1.1 Computation of Geometrical Signal Transit Time

The inputs needed for the light time algorithm (sec. 3.4) are contained in the list above. The outputs from the light time algorithm required for use in the range model are:

$\Delta t(p)$ = Signal delay time for each leg of signal path

For IDOP = 0 : p = 1,2

For IDOP = 1 : p = 1,2,3,4,5

\bar{R}_p, t_p = Position (M50 coordinate) of each point on signal path at participation time t_p

For IDOP = 0 : p = 1,2,3

For IDOP = 1 : p = 1,2,3,4,5,6

Note: The time t_1 corresponds to the receiver measurement time t_R . Figures 1 and 2 show the signal path geometry for direct and relay tracking. Section 3.4.2 gives a summary definition of the participating point indexes used here.

Compute the geometrical total signal path length (uncorrected for refraction):

$$S' = C \sum \Delta t(p) \quad \begin{cases} \text{For IDOP} = 0 : p = 1,2 \\ \text{For IDOP} = 1 : p = 1,2,3,4 \end{cases}$$

3.1.2 Application of Refraction Correction

Inputs (in addition to those given in the above list) required for the range refraction correction (sec. 3.5.1) are computed as follows:

$$\vec{r}_\rho(\text{REC}) = \bar{R}_2 - \bar{R}_1 ; \text{IDOP} = 0,1$$

$$t_{\text{REC}} = t_1$$

Receiver leg range vector (M50 coordinate) and associated time.

(Note: This vector is defined to point along the negative of the forward signal path.

$$\vec{\rho}(\overline{\text{TXM}}) = \overline{R}_{L-1} - \overline{R}_L ; \begin{cases} \text{For IDOP} = 0 : L = 3 \\ \text{For IDOP} = 1 : L = 5 \end{cases}$$

$$t_{\text{TXM}} = T_L$$

Transmitter leg range vector (M50 coordinate) and associated time.

The outputs from the range refraction correction model (sec. 3.5.1) are as follows:

$\delta\rho(\text{REC})$ = receiver leg range correction

$\delta\rho(\text{TXM})$ = transmitter leg range correction

The total (refraction corrected) range is

$$S = S' + [\delta\rho(\text{REC}) + \delta\rho(\text{TXM})]$$

FOR IDOP = 0, this is the final form of the computed range measurement.

For IDOP = 1, a further adjustment for range ambiguity must be made so that the computed relay range can be compared to the measured range. This additional computation is given below.

3.1.3 Relay Range Ambiguity Adjustment

For IDOP = 1 only, compute the ambiguous range S_A . Specifically, in terms of ON code length, $S_A = S$ modulo (PN code length in distance units).

$$S_A = S \text{ MOD}(A_R)$$

(Note: The PN code length A_R is assumed to be in internal distance units.)

Using the range observation, G_{RNG} a reasonableness test is now made to resolve any uncertainty concerning the total number of ambiguity intervals in the total signal path range.

If $|G_{\text{RNG}} - S_A| > A_R/2$ recompute S as:

$$S = S_A + \frac{G_{\text{RNG}} - S_A}{|G_{\text{RNG}} - S_A|} A_R = S_A + A_R \text{ SIGN}(G_{\text{RNG}} - S_A)$$

Otherwise: $S = S_A$

3.1.4 Residual Computation

The range residual $D(S)$ is computed from:

$$D(S) = G_{RNG} - S$$

3.2 DOPPLER MEASUREMENT MODELS

Two general forms of the Doppler measurement model will be given:

- a. Direct Doppler measurement ($IDOP = 0$); direct Doppler data includes two-way and three-way S-band measurements.
- b. Relay Doppler measurement ($IDOP = 1$); relay Doppler data include two-way/three-way and hybrid relay measurements for both S-band and Ku-band frequencies.

In both cases, the computed Doppler measurement is the average frequency shift in a transmitted reference signal, corrected for tropospheric refraction (on the signal-path legs between ground stations and space vehicle) and any known bias. In the case of relay Doppler, an additional term due to the frequency shift in the pilot tone signal at the receiver is added so that the computed measurement will be comparable to the radar observation.

The differenced-range form of the Doppler measurement model is used for all cases. This means that light time solutions must be obtained for both the "start" and "end" times of the receiver count interval. Because Doppler observations in a given data batch are (for the most part) contiguous, computations for the end time of one count interval (measurement) will often be valid for the start time of the next count interval.

Signal-path configurations for direct and relay Doppler measurements are shown in figures 1 and 2. A summary table that defines each of the participating points along the signal path and the point index notation convention is given in section 3.4.

Input parameters required for the Doppler measurement models are listed as follows:

$IDOP$ = Flag that defines tracking configuration
 0 = direct tracking: 1 = relay tracking

t_R = Doppler measurement time (corresponds to end time of measurement count interval)

τ = Count interval (averaging time of measurement)

- ν_{NX} = Reference frequency; for direct tracking, ν_{NX} is the transmitter frequency; for relay tracking, ν_{NX} is the target vehicle (user spacecraft) transmit frequency under zero-Doppler conditions.
- K = Doppler frequency model multiplier;
For direct tracking (S-band), K is the composite of the target vehicle transponder multiplier and the Doppler extractor multiplier (nominal value is $1000 \times 240/221$). For relay tracking, K is the Doppler extractor multiplier (nominal values are 1000 for S-band and 100 for Ku-band).
- ω_3 = Offset frequency in Doppler extractor (nominal value is 240 MHz)
- (bF_p) = Return link TDRS translation frequency; (sometimes called return link pilot tone bias frequency)
- b_D = Relay Doppler measurement bias from current estimate of state vector

Inputs required for light time algorithm; these parameters are defined in detail in section 3.4. They are summarized here for reference as follows:

$(\lambda_R, r_{GR}, z_{GR}, \phi_{DR})$ = receiver location parameters

$(\lambda_X, r_{GX}, z_{GX}, \phi_{DX})$ = transmitter location parameters

$\overline{EPH}(I)$ = nine-point ephemeris tables ($I = 1, 2, 3$)

Inputs required for refraction correction model; these parameters are defined in detail in section 3.5 and are summarized here for reference.

N_R = Refraction modulus at receiver

H_R = Scale height for receiver

N_X = Refraction modulus at transmitter

H_X = Scale height for transmitter

REFIND = Low-speed refraction correction indicator.

Parameters obtained from system interfaces

C = Velocity of light

G_{DOP} = Doppler measurement

3.2.1 Computation of Signal Delay Times at Start and End of Count Interval

The light time algorithm (sec. 3.4) must be exercised for both start and end times of the count interval. These times at the receiver are:

$$t_1^{(e)} = t_R \quad (\text{End time of receiver count interval})$$

$$t_1^{(s)} = t_R - \tau \quad (\text{Start time of receiver count interval})$$

Each of these times (along with IDOP, station parameters, and ephemeris parameters listed above) are provided to the light time algorithm. The two sets of outputs, corresponding to the start and end times of the receiver count interval (indicated by superscripts (s) and (e)) are as follows:

$$\Delta t^{(s)}(p) ; \Delta t^{(e)}(p) = \text{signal delay times for each signal leg}$$

$$\text{For IDOP} = 0 : p = 1, 2$$

$$\text{For IDOP} = 1 : p = 1, 2, 3, 4, 5$$

$$\bar{R}_p^{(s)}, t_p^{(s)} ; R_p^{(e)}, t_p^{(e)} = \text{position (M50 coordinates) and epoch of each point on signal path at participation times}$$

$$\text{For IDOP} = 0 : p = 1, 2, 3$$

$$\text{For IDOP} = 1 : p = 1, 2, 3, 4, 5, 6$$

Note: For a given data batch, the light time algorithm outputs generated from $t_1^{(e)}$ = (end time of current measurement count interval) should be saved. Very often, the start time of the next measurement count interval will be this same time, in which case an entire light time computation cycle can be eliminated.

3.2.2 Basic (Uncorrected) Differenced-Range Doppler Models

The Doppler models, before correction for refraction and bias are computed as follows.

a. Direct tracking (IDOP = 0)

$$f' = \omega_3 - \frac{K v_{NX}}{\tau} \sum_{p=1}^2 [\Delta t^{(e)}(p) - \Delta t^{(s)}(p)]$$

Note: For three-way direct tracking (incoherent), a term

$$+ K (\nu_{NX} - \nu_{NR})$$

is often included in the equation for f' . This term accounts for the possibility of a different reference frequency, ν_{NR} , in the Doppler extractor at the receiver. Because three-way direct tracking configurations are set up so that nominally $\nu_{NR} = \nu_{NX}$, this term is not included, and any difference between the two frequencies will be accounted for in the bias correction processor (BCP). If it were desired to include this term in the program mechanization, an additional frequency ν_{NR} must be provided as an input.

b. Relay tracking (IDOP = 1)

$$f' = \omega_3 - \frac{K \nu_{NX}}{\tau} \sum_{p=1}^4 [\Delta t^{(e)}(p) - \Delta t^{(s)}(p)]$$

$$- \frac{K (bF_p)}{\tau} [\Delta t^{(e)}(5) - \Delta t^{(s)}(5) + \Delta t^{(e)}(1) - \Delta t^{(s)}(1)]$$

3.2.3 Application of Refraction and Bias Corrections

Inputs (in addition to those given in the above list) required for the Doppler refraction correction (sec. 3.5.2) are computed as follows:

$$\rho_{REC}^{(s)} = R_2^{(s)} - R_1^{(s)} ; \text{ IDOP} = 0, 1$$

$$t_{REC}^{(s)} = t_1^{(s)}$$

Receiver leg range vector (M50 coordinate) and associated time for start time of count interval. (Note that the positive sense is along the negative of the forward signal path.)

$$\vec{\rho}_{\text{REC}}^{(e)} = \vec{R}_2^{(e)} - \vec{R}_1^{(e)} ; \text{IDOP} = 0, 1$$

$$t_{\text{REC}}^{(e)} = t_1^{(e)}$$

Receiver leg range vector (M50 coordinate) for end time of count interval. (Note that the positive sense is along the negative of the forward signal path.)

$$\vec{\rho}_{\text{TXM}}^{(s)} = \vec{R}_{L-1}^{(s)} - \vec{R}_L^{(s)} ; \begin{cases} \text{For IDOP} = 0 : L = 3 \\ \text{For IDOP} = 1 : L = 5 \end{cases}$$

$$t_{\text{TXM}}^{(s)} = t_L^{(s)}$$

Transmitter leg range vector (M50 coordinate) and associated time for start time of count interval.

$$\vec{\rho}_{\text{TXM}}^{(e)} = \vec{R}_{L-1}^{(e)} - \vec{R}_L^{(e)} ; \begin{cases} \text{For IDOP} = 0 : L = 3 \\ \text{For IDOP} = 1 : L = 5 \end{cases}$$

$$t_{\text{TXM}}^{(e)} = t_L^{(e)}$$

Transmitter leg range vector (M50 coordinate) and associated time for start time of count interval.

$$\vec{\rho}_{\text{PLT}}^{(s)} = \vec{R}_2^{(s)} - \vec{R}_6^{(s)} ; \text{IDOP} = 1 \text{ only}$$

$$t_{\text{PLT}}^{(s)} = t_6^{(s)}$$

Receiver to TDRS-2 range vector (M50 coordinate) and associated time for start time of count interval.

$$\vec{\rho}_{\text{PLT}}^{(e)} = \vec{R}_2^{(e)} - \vec{R}_6^{(e)} ; \text{IDOP} = 1 \text{ only}$$

$$t_{\text{PLT}}^{(e)} = t_6^{(e)}$$

Receiver to TDRS-2 range vector (M50 coordinate) and associated time for start time of count interval.

The outputs from the Doppler refraction correction (sec. 3.5.2) are as follows:

$\delta\rho^{(s)}(\text{REC})$, $\delta\rho^{(e)}(\text{REC})$ = Range corrections for receiver leg corresponding to start and end times of count interval.

$\delta\rho^{(s)}(\text{TXM})$, $\delta\rho^{(e)}(\text{TXM})$ = Range corrections for transmitter leg corresponding to start and end times of count interval.

$\delta\rho^{(s)}(\text{PLT})$, $\delta\rho^{(e)}(\text{PLT})$ = Range corrections for pilot tone leg (receiver to TDRS-2) corresponding to start and end times of count interval. (These outputs apply for IDOP = 1 only.)

The Doppler measurement models, corrected for refraction and bias, are given by the following:

For IDOP = 0 :

$$f = f' - \frac{K \nu_{NX}}{\tau C} [\delta\rho^{(e)}(\text{REC}) - \delta\rho^{(s)}(\text{REC}) + \delta\rho^{(e)}(\text{TXM}) - \delta\rho^{(s)}(\text{TXM})]$$

For IDOP = 1 :

$$f = f' - \frac{K \nu_{NX}}{\tau C} [\delta\rho^{(e)}(\text{REC}) - \delta\rho^{(s)}(\text{REC}) + \delta\rho^{(e)}(\text{TXM}) - \delta\rho^{(s)}(\text{TXM})]$$

$$- \frac{K (bF_p)}{\tau C} [\delta\rho^{(e)}(\text{PLT}) - \delta\rho^{(s)}(\text{PLT}) + \delta\rho^{(e)}(\text{REC}) - \delta\rho^{(s)}(\text{REC})]$$

$$+ b_D$$

Note: The units of the computed Doppler measurement will be the same as the internal units of the frequencies ν_{NX} , (bF_p) , and b_D . The internal units of these parameters are expected to be Hz.

3.2.4 Residual Computation

The Doppler residual $D(f)$ is computed from:

$$D(f) = G_{DOP} - f$$

3.3 ANGLE MEASUREMENT MODELS

Angle measurements apply only to direct tracking (IDOP = 0). The three types of angle measurement sets considered here are as follows:

- a. A,E = Azimuth and elevation angles
(see figure 3 for applicable geometry)
- b. $X_{N/S}, Y_{N/S}$ = X-Y angles for a north/south antenna mount
(see figure 4 for applicable geometry)
- c. $X_{E/W}, Y_{E/W}$ = X-Y angles for an east/west antenna mount
(see figure 5 for applicable geometry)

Angle measurements apply only to receiver leg of the signal path (fig. 1), and are computed from the relative range vector $\vec{\rho}(\text{REC}) = R_2 - R_1$, which corresponds to the receiver measurement time t_R . The equations used to compute $\vec{\rho}(\text{REC})$ are identical for all three angle measurement sets and are also the same as those used to compute $\vec{\rho}(\text{REC})$ in the range measurement model (sec. 3.1) and $\vec{\rho}^{(e)}(\text{REC})$ in the Doppler measurement model (sec. 3.2). (As mentioned in section 3.0, signal delay times and relative range vectors for receiver time t_R are valid for all of the data types that have t_R as their receiver measurement time.)

The general computation procedure for each of the angle measurement sets is:

- a. Use output from light time algorithm (sec. 3.4) to construct the receiver leg range vector, $\vec{\rho}(\text{REC})$ in M50 coordinates.
- b. Rotate $\vec{\rho}(\text{REC})$ to station-centered ENU topodetic coordinates (use transformation of section 3.6).
- c. Use ENU components ξ, η, ζ to compute the uncorrected angle measurements.
- d. Use elevation refraction correction model (sec. 3.5.3) to compute elevation correction δE . Use δE to compute the refraction corrections for the angle measurements.

Input parameters required for the angle measurement models are listed as follows:

IDOP = 0 , Direct tracking only

t_R = Receiver measurement time

GANG1, GANG2 = Angle observations

GANG1 corresponds to azimuth or an X angle

GANG2 corresponds to elevation or a Y angle

Inputs required for light time algorithm

These parameters are defined in detail in section 3.4. They are summarized here for reference:

$(\lambda_R, r_{GR}, Z_{GR}, \phi_{DR})$ = Receiver location parameters

$(\lambda_X, r_{GX}, Z_{GX}, d_{PX})$ = Transmitter location parameters

$\overline{EPH}(I)$ = Nine-point ephemeris tables ($I = 1, 2, 3$)

Inputs required for refraction correction model

These (station characteristics) parameters are defined in detail in section 3.5. They are summarized for reference as follows:

N_R = Refraction modulus at receiver

H_R = Scale height for receiver

N_X = Scale height for transmitter

H_X = Scale height for transmitter

REFIND = Low-speed refraction correction indicator

Parameters obtained from system interfaces

C = Velocity of light

3.3.1 A,E Angle Measurement Models

Many of the steps in this computational procedure are identical to those used for the two X-Y angle models, and the procedure for computation of the elevation angle, E, is used in all of the refraction correction models of section 3.5. For these reasons, the steps in this computational procedure are numbered (1), (2), etc., so that they may be referenced in subsequent sections.

The computational procedure is as follows:

- (1) Provide IDOP, t_R , and the inputs listed above to the light time algorithm (sec. 3.4) and obtain the outputs:

$\Delta t(p)$; ($p = 1$) = Signal delay times

\bar{R}_p, t_p ; ($p = 1, 2$) = Position (M50 coordinate) and epoch of each point on signal path

- (2) Compute the receiver leg range vector.

$$\vec{\rho}(\text{REC}) = \bar{R}_2 - \bar{R}_1$$

$$t_{\text{REC}} = t_1$$

- (3) Rotate $\vec{\rho}(\text{REC})$ to ENU-topodetic coordinates using the procedure of section 3.6, and obtain the ENU components:

$(\xi, \eta, \zeta) = \text{ENU-topodetic components of receiver leg range vector,}$
 $\vec{\rho}(\text{REC})$

- (4) Compute (uncorrected) elevation angle:

$$E' = \text{SIN}^{-1} \left[\frac{\zeta}{\rho} \right], \quad E' \in [0, 2\pi]$$

$$\rho = (\xi^2 + \eta^2 + \zeta^2)^{1/2}$$

- (5) Compute azimuth angle:

$$A = \text{TAN}^{-1} \frac{\xi}{\eta}$$

$A \in [0, 2\pi]$, i.e., negative angles not allowed

- (6) Provide E' , $\Delta t(1)$, and the station characteristics parameters listed above to the elevation refraction correction model (sec. 3.5.3.1) and obtain the following:

$\delta E = \text{elevation refraction correction}$

- (7) Compute the corrected A, E angles:

$$E = E' + \delta E$$

$$A = A \quad (\text{no correction required})$$

(8) Compute residuals

$$\left. \begin{aligned} D(A) &= G_{ANG1} - A \\ D(E) &= G_{ANG2} - E \end{aligned} \right\} \quad \text{If } |D| > \pi : \text{ recompute as} \\ D \rightarrow D - 2\pi \text{ SIGN}(D)$$

3.3.2 $X_{N/S}, Y_{N/S}$ Angle Measurement Models

The computational procedure is as follows:

a. Perform steps (1) through (4) of section 3.3.1 to obtain the following:

$\Delta t(1)$ = Receiver leg delay time

E' = Elevation angle (uncorrected)

(ξ, η, ζ) = receiver leg range vector components in ENU-topedetic coordinates.

b. Compute (uncorrected) angles

$$X'_{N/S} = \tan^{-1} \left[\frac{\xi}{\zeta} \right]$$

$$X'_{N/S} \in [0, 2\pi]$$

(i.e., if arc tangent yields a negative angle, add 2π)

$$Y'_{N/S} = \sin^{-1} \left[\frac{\eta}{\rho} \right], \quad \rho = (\xi^2 + \eta^2 + \zeta^2)^{1/2}$$

$$Y'_{N/S} \in [0, 2\pi]$$

(i.e., if arc sine yields a negative angle, add 2π)

c. Provide E' , $\Delta t(1)$, and the station characteristics parameters listed above to the elevation refraction correction model (sec. 3.5.3) and obtain the following:

δE = elevation refraction correction

d. Compute the $X_{N/S}, Y_{N/S}$ refraction corrections:

$$\delta X_{N/S} = - \frac{\xi \rho^2 \delta E}{(\xi^2 + \eta^2)^{1/2} (\zeta^2 + \xi^2)} = \frac{-\sin X_{N/S} \delta E}{\cos Y_{N/S} [1 - \cos^2 X_{N/S} \cos^2 Y_{N/S}]^{1/2}}$$

$$\delta Y_{N/S} = - \frac{\eta \zeta \delta E}{(\xi^2 + \eta^2)^{1/2} (\zeta^2 + u^2)^{1/2}} = \frac{-\cos X_{N/S} \sin Y_{N/S} \delta E}{[1 - \cos^2 X_{N/S} \cos^2 Y_{N/S}]^{1/2}}$$

- e. Compute the corrected $X_{N/S}, Y_{N/S}$ angles:

$$X_{N/S} = X'_{N/S} + \delta X_{N/S}$$

$$Y_{N/S} = Y'_{N/S} + \delta Y_{N/S}$$

- f. Compute residuals

$$\left. \begin{aligned} D(X_{N/S}) &= G_{ANG1} - X_{N/S} \\ D(Y_{N/S}) &= G_{ANG2} - Y_{N/S} \end{aligned} \right\} \text{ If } |D| > \pi : \text{recompute as } D \rightarrow D - 2\pi \text{ SIGN}(D)$$

3.3.3 $X_{E/W}, Y_{E/W}$ Angle Measurement Models

This computation is virtually the same as in the previous section; only the forms of the equations for the computed angles and their refraction corrections are changed. The computation procedure is as follows:

- a. Perform steps (1) through (4) of section 3.3.1 to obtain the following:

$\Delta t(1)$ = Receiver leg delay time

E' = Elevation angle (uncorrected)

(ξ, η, ζ) = Receiver range vector components in ENU-topodetic coordinates

- b. Compute (uncorrected) angles

$$X'_{E/W} = \text{TAN}^{-1} \left[\frac{-\eta}{\zeta} \right]$$

$$X'_{E/W} \in [0, 2\pi]$$

(i.e., if arc tangent yield a negative angle, add 2π)

$$Y'_{E/W} = \text{SIN}^{-1} \left[\frac{\xi}{\rho} \right], \quad \rho = [\xi^2 + \eta^2 + \zeta^2]^{1/2}$$

$$Y'_{E/W} \in [0, 2\pi]$$

(i.e., if arc sine yields a negative angle, add 2π)

- c. Provide E' , $\Delta t(1)$, and the station characteristics parameters listed above to the elevation refraction correction model (sec. 3.5.3) and obtain:

δE = Elevation refraction correction

- d. Compute the $X_{E/W}, Y_{E/W}$ refraction corrections as follows:

$$\delta X_{E/W} = \frac{\eta^2 \delta E}{(\xi^2 + \eta^2)^{1/2} (\eta^2 + \zeta^2)} = \frac{-\sin X_{E/W} \delta E}{\cos Y_{E/W} [1 - \cos^2 X_{E/W} \cos^2 Y_{E/W}]^{1/2}}$$

$$\delta Y_{E/W} = \frac{\xi \zeta \delta E}{(\xi^2 + \eta^2)^{1/2} (\eta^2 + \zeta^2)^{1/2}} = \frac{-\cos X_{E/W} \sin Y_{E/W} \delta E}{[1 - \cos^2 X_{E/W} \cos^2 Y_{E/W}]^{1/2}}$$

- e. Compute the corrected $X_{E/W}, Y_{E/W}$ angles:

$$X_{E/W} = X'_{E/W} + \delta X_{E/W}$$

$$Y_{E/W} = Y'_{E/W} + \delta Y_{E/W}$$

- f. Compute residuals

$$\left. \begin{aligned} D(X_{E/W}) &= G_{ANG1} - X_{E/W} \\ D(Y_{E/W}) &= G_{ANG2} - Y_{E/W} \end{aligned} \right\} \text{ If } |D| > \pi : \text{ recompute as } D \rightarrow D - 2\pi \text{ SIGN}(D)$$

3.4 LIGHT TIME ALGORITHM

The light time algorithm computes the time required for an electromagnetic signal to traverse the distance between two points in the signal-path configuration (i.e., the positions of the two participants at their times of participation). The light time problem is solved by using an iterative technique to compute the required times, positions, and velocities for the participants in each of the signal-path segments. The light time algorithm is applied successively to each leg of the signal path, beginning with the last leg, where the receiver time, position, and velocity are known.

The direct tracking data configuration (fig. 1) provides the simplest example of the light time problem solution. In this tracking configuration, a signal is sent from a ground transmitter at time t_3 ; it is received and retransmitted from the spacecraft at time t_2 , and is subsequently received at a ground receiving station at time t_R . Starting with the known reception time t_R , the light time equation is solved by an iterative technique for the signal-path segment from the spacecraft to the receiving station (this path segment is sometimes referred to as the receiver leg). This provides the time of participation of the spacecraft t_2 . Given t_2 , the light time equation is solved iteratively for the signal-path segment from the spacecraft to the ground transmitting station (this path segment is sometimes referred to as the transmitter leg). This provides the time of participation of the ground transmitter t_3 . The position vectors of the various participating elements at their time of participation are output by the light time algorithm as a by-product of the iteration procedure.

The same techniques and procedures are used for the relay data configuration (fig. 2) but are more complicated in that five signal-path segments are involved.

The light time algorithm requires the actual data measurement time t_R , station characteristics information for each of the participating ground stations, the appropriate spacecraft ephemerides, and a tracking data configuration flag. All output vectors are referenced to the Aries mean-of-1950 (M50) Cartesian coordinate system.

a. Signal path configurations

The light time algorithm is capable of processing direct (two-way and three-way) and relayed (two-way/three-way and hybrid) data. These four configurations can be reduced to two by implementing the assumption that (1) both the receiver and the transmitter parameters shall be addressed even if they are the same, and (2) both TDRS ephemerides shall be addressed even if they are the same.

In the relay tracking configuration, the light time algorithm computes the signal times for each of the normal four signal-path legs (fig. 2); however, the TDRS system requires that an extra "fifth leg" light time be computed. (This extra fifth leg corresponds to the pilot tone signal that is sent from the receiver (point 6 in signal path of figure 2) to the return-link TDRS (point 2 on the signal path of figure 2) and is subsequently returned to the receiver at normal data receive time t_R .)

The two tracking configurations (direct and relay) are presented in figures 1 and 2.

The indexes p used for the participating points along the signal path and the applicable ephemeris $\overline{EPH}(I)$ are defined in the following table:

Tracking configuration	IDOP	Participating point index					
		1	2	3	4	5	6
Direct	0	REC	VEH	TXM			
			$\overline{EPH}(1)$				
Relay	1	REC	TDRS-2	VEH	TDRS-1	TXM	REC
			$\overline{EPH}(2)$	$\overline{EPH}(2)$	$\overline{EPH}(3)$		(for pilot tone)

Note: For relay tracking, there are always two TDRS ephemerides; in the case of two-way relay tracking, $\overline{EPH}(1)$ and $\overline{EPH}(3)$ are the same.

b. Input parameters required for light time algorithm

IDOP = Flag that identifies tracking configuration

0 = direct, 1 = relay

t_R = Measurement time at receiver

$(\lambda_R, r_{GR}, Z_{GR}, \phi_{DR})$ = Receiver coordinates

λ = longitude east of Greenwich

r_G = distance from Earth polar axis

Z_G = distance above equator

ϕ_D = geodetic latitude

$(\lambda_X, r_{GX}, Z_{GX}, \phi_{DX})$ = Transmitter coordinates

$\overline{EPH}(I)$ = Nine-point ephemeris tables (roughly centered at t_R) that contain time, position (M50 coordinate), and velocity (M50 coordinate) of the orbiting satellites indicated by the index (I).

For IDOP = 0 :

$\overline{\text{EPH}}(1)$ = target vehicle ephemeris
tables for I = 2,3 are blank

For IDOP = 1 :

$\overline{\text{EPH}}(1)$ = TDRS-2 ephemeris

$\overline{\text{EPH}}(2)$ = target vehicle ephemeris

$\overline{\text{EPH}}(3)$ = TDRS-1 ephemeris

Parameters obtained from system interfaces:

ω = Mean sidereal Earth rate

C = Velocity of light

$[\text{RNP}]$ = Matrix that transforms from M50 coordinates to TEI coordinates
at the requested time of interest.

3.4.1 Receiver Position Computation

The receiver position vector \vec{R}_1 (in M50 coordinates) is computed at the receive time t_R . The coordinate systems and transformations used here are defined in volume XIV of these requirements.

From the receiver parameters ($\lambda_R, r_{GR}, Z_{GR}, \phi_{DR}$), compute the receiver position \vec{P}_{REC} in TEI coordinates:

$$\vec{P}_{\text{REC}}(t_R) = \begin{bmatrix} r_{GR} \cos (\lambda_R + \omega t_R) \\ r_{GR} \sin (\lambda_R + \omega t_R) \\ Z_{GR} \end{bmatrix}$$

Rotate \vec{P}_{REC} to M50 coordinates, using the $[\text{RNP}]$ matrix for time t_R .

$$\vec{R}_1(t_R) = [\text{RNP}]^T \vec{P}_{\text{REC}}(t_R)$$

3.4.2 Computation of Signal Delay Times

These computations are essentially the same for both direct and relay tracking. The signal times $\Delta t(p)$ for each leg of the signal path (beginning with $p = 1$, where the receiver time t_R is known) are computed via the iterative procedure defined in section 3.4.3. Except for the final (transmitter) leg of the signal

path, M50 coordinates are used. For this final leg, the transmitter position is computed in TEI coordinates, and the signal time itself is computed using these coordinates. For relay tracking (IDOP = 1), an additional delay time $\Delta t(5)$ is computed (this is the time associated with the transmitted pilot tone signal from the receiver to TDRS-2).

a. Computation of $\Delta t(p)$ for all but final signal legs:

For direct tracking (IDOP = 0), compute $\Delta t(1)$:

- (1) Interpolate the values of the components of $\bar{R}_2(t_R)$ from EPH(1)
- (2) Initialize the iterative computation of section 3.4.3 with

$$t_A = t_R, \bar{R}(0) = \bar{R}_2(t_R), \bar{R}_A = \bar{R}_1(t_R) \text{ and obtain:}$$

$$\Delta t(1) = \text{Signal delay time}$$

$$t_2 = t_R - \Delta t(1), \text{ Time of vehicle participation}$$

$$\bar{R}_2(t_2) = \text{Position of vehicle at time } t_2$$

For relay tracking (IDOP = 1), compute $\Delta t(1)$, $\Delta t(2)$, $\Delta t(3)$: The following procedure is applied successively for $p = 1, 2, 3$ using the results from the previous computation to initialize the current computation. (This procedure will be recognized as the generalization of that given above for direct tracking.)

Compute the following for $p = 1, 2, 3$.

Initial values: $t_1 = t_R$, $\bar{R}_1(t_1) = \bar{R}_1$

- (1) Interpolate $\bar{R}_{p+1}(t_p)$ from $\overline{EPH}(p)$
- (2) Initialize the iterative computation of section 3.1.6 with

$$t_A = t_p, \bar{R}(0) = \bar{R}_{p+1}(t_p), \bar{R}_A = \bar{R}_p(t_p) \text{ and obtain}$$

$$\Delta t(p) = \text{signal delay time}$$

$$t_{p+1} = \text{time of participation of point } p+1$$

$$\bar{R}_{p+1}(t_{p+1}) = \text{position (M50 coordinate) of point } p+1 \text{ at participation time}$$

b. Computation of Δt for final signal leg:

This computation is the same for both direct and relay tracking with this understanding in the equations that follow.

For direct tracking (IDOP = 0) : m = 2

For relay tracking (IDOP = 1) : m = 4

- (1) Compute transmitter position \bar{P}_{TXM} (in TEI coordinates) at time t_m .
Use the transmitter parameters $(\lambda_X, r_{GX}, z_{GX}, \phi_{DX})$ to obtain

$$\bar{P}_{TXM}(t_m) = \begin{bmatrix} r_{GX} \cos (\lambda_X + \omega t_m) \\ r_{GX} \sin (\lambda_X + \omega t_m) \\ z_{GX} \end{bmatrix}$$

- (2) Rotate the M50 position vector $R_m(t_m)$ to TEI coordinates;
use $[RNP]$ matrix for time t_m .

$$\bar{P}_m(t_m) = [RNP]^T \bar{R}_m(t_m)$$

- (3) Initialize the iterative computation of section 3.4.3 with

$t_A = t_m$, $\bar{R}(0) = \bar{P}_{TXM}(t_m)$, $\bar{R}_A = \bar{P}_m(t_m)$ and obtain the following:

$\Delta t(m+1)$ = Signal delay time for transmitter leg

t_{m+1} = Time of participation of point m+1 (transmitter)

$\bar{P}_{m+1}(t_{m+1})$ = Position (TEI coordinate) of point m+1 at time t_{m+1}

- (4) Rotate transmitter position, $\bar{P}_{m+1}(t_{m+1})$ to M50 coordinates

$$\bar{R}_{m+1}(t_{m+1}) = [RNP] \bar{P}_{m+1}(t_{m+1})$$

c. Computation of $\Delta t(5)$ for relay tracking:

For relay tracking (IDOP = 1) cases only, the pilot tone delay time $\Delta t(5)$ is computed using the same procedure as defined above for the final signal leg. Recall that t_2 , $\bar{R}_2(t_2)$ and $\bar{P}_{REC}(t_R)$ have already been computed. (For convenience, set $p = 5$ for use in the iterative computation of section 3.4.3.)

- (1) Rotate the M50 position vector $\bar{R}_2(t_2)$ to TEI coordinates; use $[RNP]$ matrix for time t_2 .

$$\bar{P}_2(t_2) = RNP^T \bar{R}_2(t_2)$$

- (2) Initialize the iterative computation of section 3.4.3 with

$$t_A = t_2, \bar{R}(0) = \bar{P}_{REC}(\bar{t}_R), \bar{R}_A = \bar{P}_2(t_2) \text{ and obtain the following:}$$

$\Delta t(5)$ = Signal delay time

t_6 = Time of participation of receiver for pilot tone transmit

$\bar{P}_6(t_6)$ = Position (TEI coordinates) of receiver at time t_6

- (3) Rotate the position vector $\bar{P}_6(t_6)$ to M50 coordinates

$$\bar{R}_6(t_6) = [RNP] \bar{P}_6(t_6)$$

Computation of target vehicle velocity (M50 coordinates) at vehicle participation time:

The position and velocity of the target vehicle, at vehicle participation, will be required for later computations. The vehicle positions have already been obtained; they are

$$\bar{R}_2(t_2) \text{ for IDOP} = 0$$

$$\bar{R}_3(t_3) \text{ for IDOP} = 1$$

The appropriate ephemeris is interpolated to obtain the corresponding velocities

For IDOP = 0 : Interpolate $\overline{EPH}(1)$ at time t_2 to obtain $\bar{V}_2(t_2)$;

For IDOP = 1 : Interpolate $\overline{EPH}(2)$ at time t_3 to obtain $\bar{V}_3(t_3)$

3.4.3 Iterative Computation Procedure

The inputs required to initialize the iterative computation of Δt are defined in section 3.4.2 above. The symbols used here (and in section 3.4.2) are

t_A = Known time of fixed end point

\bar{R}_A = Known position of fixed end point (at time t_A)

$\bar{R}(0)$ = Initial estimate of "unknown" end-point position

IDOP and p = Flags that indicate the ephemeris (\overline{EPH}) or station parameters to be used (table 3.4.3-I)

The outputs of the iterative computation are as follows:

Δt = Signal delay time

$t = t_A - \Delta t$

$\bar{R}(t)$ = Final (converged) solution for unknown end-point position

The computation procedure depends on whether the unknown end point is an orbiting satellite or a ground station. The required logical decision can be made with the aid of table 3.4.3-I.

TABLE 3.4.3-I.- COMPUTATION PROCEDURE

P =	1	2	3	4	5
IDOP = 0	$\overline{EPH}(1)$	TXM			
IDOP = 1	$\overline{EPH}(1)$	$\overline{EPH}(2)$	$\overline{EPH}(3)$	TXM	REC

If the combination of "values" of IDOP and p indicate an ephemeris $\overline{EPH}(x)$, that ephemeris is to be used in the computations. If a ground station, REC or TXM, is indicated by table 3.1.6, the indicated "station parameters" are to be used in the computations.

- a. If the unknown end point is an orbiting satellite (table 3.4.3-I indicates $\overline{EPH}(x)$), the following computation procedure is used for the j^{th} iteration.

$$\rho(j) = |\bar{R}(j-1) - \bar{R}_A|$$

$$\Delta t(j) = \rho(j)/C \quad (C = \text{velocity of light})$$

$$t(j) = t_A - \Delta t(j)$$

Interpolate $\bar{R}(j)$, at time $t(j)$, from $\overline{EPH}(x)$

Test: If $|t(j) - t(j-1)| < 3 \times 10^{-13}$ HR, or $j = 6$, cease computation and set output values as follows:

$$\Delta t = \Delta t(j)$$

$$t = t(j)$$

$$\bar{R}(t) = \bar{R}(j)$$

Otherwise: Repeat computations with $j \rightarrow j+1$

- b. If the "unknown" end point is a ground station (table 3.4.3 indicates REC or TXM), the following computation procedure is used for the j^{th} iteration.

$$\rho(j) = |\bar{R}(j-1) - \bar{R}_A|$$

$$\Delta t(j) = \rho(j)/C$$

$$t(j) = t_A - \Delta t(j)$$

Use indicated "station parameters" $(\lambda, r_G, Z_G, \phi_D)$, to compute

$$\bar{R}(j) = \begin{bmatrix} r_G \cos [\lambda + \omega t(j)] \\ r_G \sin [\lambda + \omega t(j)] \\ Z_G \end{bmatrix}$$

Test: If $|t(j) - t(j-1)| < 3 \times 10^{-13}$ HR, or $j = 6$, cease computation and set output values as follows:

$$\Delta t = \Delta t(j)$$

$$t = t(j)$$

$$\bar{R}(t) = \bar{R}(j)$$

3.4.4 Outputs from Light Time Algorithm

The outputs from the computations of this section are as follows:

- a. $t(p)$ = Signal delay times for each leg of signal path.

For IDOP = 0 : $p = 1, 2$

For IDOP = 1 : $p = 1, 2, 3, 4, 5$

- b. $\bar{V}_Q(t_Q)$ = Velocity (M50 coordinate) of target vehicle at participation time t_Q .

For IDOP = 0 ; $Q = 2$

For IDOP = 1 : $Q = 3$

- c. $\bar{R}_p(t_p), t_p$ = Position (M50 coordinates) and epoch of all points on signal path at participation time t_p .

For IDOP = 0 : $p = 1, 2, 3$

For IDOP = 1 : $p = 1, 2, 3, 4, 5, 6$

Note: The time t_1 corresponds to the receiver measurement time t_R , which is an input. See section 3.4 for a summary definition of the participating point indices for the direct and relay tracking configurations.

3.5 REFRACTION CORRECTION MODELS

The refraction correction models for range, Doppler, and elevation angle measurements are given in this section. The inputs required to exercise each of these models are provided in the corresponding measurement models (sec. 3.1, 3.2, 3.3).

A complete list of input parameters for the refraction correction models is as follows:

- a. IDOP = Flag that defines tracking configuration

- b. Station characteristics

N_R = Refraction modulus at receiver

H_R = Atmospheric scale height for receiver

N_X = Refraction modulus at transmitter

H_X = Atmospheric scale height for transmitter

These parameters are stored as average values for each calendar month of the year. For a differential correction (or residual computation) for a given data arc, the values of these parameters valid for the anchor time of that data arc are used for all computations; i.e., it is not necessary to "switch" values within a data arc that contains 0^h of the first day of a month.

c. Station location parameters

(used for M50 to ENU-topodetic transformation)

$(\lambda_R, r_{GR}, Z_{GR}, \phi_{DR})$ = Receiver parameters

$(\lambda_X, r_{GX}, Z_{GX}, \phi_{DX})$ = Transmitter parameters

d. Parameters obtained from system interfaces

C = Velocity of light

R_0 = Equatorial radius of reference ellipsoid

e. Inputs for range refraction correction model

(computed in section 3.1)

$\vec{\rho}_{REC}, t_{REC}$ = Receiver leg range vector (M50 coordinate) and time

$\vec{\rho}_{TXM}, t_{TXM}$ = Transmitter leg range vector (M50 coordinate) and time

f. Inputs for Doppler refraction correction model

(computed in section 3.2)

$\vec{\rho}_{REC}^{(s)}, t_{REC}^{(s)}$ = Receiver leg range vector (M50 coordinate) and time for start time of count interval

$\vec{\rho}_{REC}^{(e)}, t_{REC}^{(e)}$ = Receiver leg range vector (M50 coordinate) and time for end time of count interval

$\vec{\rho}_{TXM}^{(s)}, t_{TXM}^{(s)}$ = Transmitter leg range vector (M50 coordinate) and time for start time of count interval

$\vec{\rho}_{TXM}^{(e)}, t_{TXM}^{(s)}$ = Transmitter leg range vector (M50 coordinate) and time for end time of count interval

$\vec{\rho}_{PLT}^{(s)}, t_{PLT}^{(s)}$ = Receiver to TDRS-2 range vector (M50 coordinate) and time for start time of count interval (IDOP = 1 only)

$\vec{\rho}_{PLT}^{(e)}, t_{PLT}^{(e)}$ = Receiver to TDRS-2 range vector (M50 coordinate) and time for end time of count interval (IDOP = 1 only)

g. Inputs for elevation refraction correction model

(computed in section 3.3)

E' = Geometric elevation angle for receiver leg

$\Delta t(1)$ = Signal time for receiver leg

3.5.1 Range Refraction Correction Model

Range refraction corrections for the receiver and transmitter legs are computed from the following procedure:

- a. Rotate the receiver and transmitter range vectors, $\vec{\rho}_{REC}$ and $\vec{\rho}_{TXM}$, to ENU-topodetic coordinates using the procedure of section 3.6. Obtain the following ENU components:

$(\xi, \eta, \zeta)_{REC}$ = ENU-topodetic components of $\vec{\rho}_{REC}$

$(\xi, \eta, \zeta)_{TXM}$ = ENU-topodetic components of $\vec{\rho}_{TXM}$

- b. Compute the geometrical elevation angles, $E'(REC)$ and $E'(TXM)$, from the ENU components. Each of these elevations is given by:

$$E' = \sin^{-1} \left[\frac{\zeta}{\rho} \right], \quad \rho = \left[\xi^2 + \eta^2 + \zeta^2 \right]^{1/2}$$

(Note: This computation is the same as step (4) of section 3.3.1)

- c. Compute the approximate range corrections $\delta \rho_A(REC)$ and $\delta \rho_A(TXM)$ from the equations:

$$\delta\rho_A(\text{REC}) = \frac{2 N_R H_R}{\left[\sin^2 E'(\text{REC}) + 2 H_R/R_O\right]^{1/2} + \sin E'(\text{REC})}$$

$$\delta\rho_A(\text{TXM}) = \frac{2 N_X H_X}{\left[\sin^2 E'(\text{TXM}) + 2 H_X/R_O\right]^{1/2} + \sin E'(\text{TXM})}$$

d. Compute the range corrections, $\delta p(\text{REC})$ and $\delta p(\text{TXM})$ from:

$$\delta p(\text{REC}) = \delta\rho_A(\text{REC}) \left\{ 1 - a N_R^{3/2} \frac{H_R}{R_O} \left[\cos E'(\text{REC}) \right]^{b N_R} \right\}$$

$$\delta p(\text{TXM}) = \delta\rho_A(\text{TXM}) \left\{ 1 - a N_X^{3/2} \frac{H_X}{R_O} \left[\cos E'(\text{TXM}) \right]^{b N_X} \right\}$$

$$a = .27 \times 10^8, \quad b = 1.4 \times 10^6$$

3.5.2 Doppler Refraction Correction Model

For the differenced-range Doppler models of section 3.1.2, the range refraction corrections (corresponding to both the "start" and "end" times of the count interval) are required for each signal leg connected to a ground station.

For direct tracking (IDOP = 0), the procedure of section 3.5.1 (range refraction model) is applied twice; once for the end time of the count interval, and once for the start time of the count interval. As in the case of the measurement models, there are often computations that may be used for the following:

- a. The Doppler measurement time $t_R = t_1^{(e)}$ will often be the same as a range measurement time. The range refraction corrections corresponding to this time can be used for both the range and Doppler models.
- b. For contiguous Doppler measurements, the range refraction corrections for the start time of a given count interval will be the same as those for the end time of the previous interval.

For relay tracking (IDOP = 1), the comments above apply, with the additional computation of the range refraction corrections (start and end times) for the pilot tone signal leg.

The computational procedure is as follows. It is understood that each computation applies to both the start and end time of the count interval, so that the superscripts (s) and (e) have been omitted.

- a. Rotate the input range vectors to ENU-topodetic coordinates using the procedure of section 3.6. Obtain the following sets (for both start and end times) of ENU components:

$$(\xi, \eta, \zeta)_{\text{REC}} = \text{ENU-topodetic components of } \vec{\rho}(\text{REC})$$

$$(\xi, \eta, \zeta)_{\text{TXM}} = \text{ENU-topodetic components of } \vec{\rho}(\text{TXM})$$

$$(\xi, \eta, \zeta)_{\text{PLT}} = \text{ENU-topodetic components of } \vec{\rho}(\text{PLT})$$

for IDOP = 1 only

- b. Compute the geometrical elevation angles

E' (REC) for start and end times

E' (TXM) for start and end times

E' (PLT) for start and end times (IDOP = 1 only)

Each of these elevations is given by the following:

$$E' = \sin^{-1} \left[\frac{\zeta}{\rho} \right], \quad \rho = \left[\xi^2 + \eta^2 + \zeta^2 \right]^{1/2}$$

(Note: This computation is the same as step (4) of section 3.3.1)

- c. Compute the approximate range corrections for start and end times as follows:

$$\delta \rho_A(\text{REC}) = \frac{2 N_R H_R}{\left[\sin^2 E'(\text{REC}) + 2 H_R/R_O \right]^{1/2} + \sin E'(\text{REC})}$$

$$\delta \rho_A(\text{TXM}) = \frac{2 N_X H_X}{\left[\sin^2 E'(\text{TXM}) + 2 H_X/R_O \right]^{1/2} + \sin E'(\text{TXM})}$$

$$\delta \rho_A(\text{PLT}) = \frac{2 N_R H_R}{\left[\sin^2 E'(\text{PLT}) + 2 H_R/R_O \right]^{1/2} + \sin E'(\text{PLT})}$$

(for IDOP = 1 only)

d. Compute the range corrections (for start and end times) from:

$$\delta\rho(\text{REC}) = \delta\rho_A(\text{REC}) \left\{ 1 - a N_R^{3/2} \frac{H_R}{R_O} [\cos E'(\text{REC})]^{bN_R} \right\}$$

$$\delta\rho(\text{TXM}) = \delta\rho_A(\text{TXM}) \left\{ 1 - a N_X^{3/2} \frac{H_X}{R_O} [\cos E'(\text{TXM})]^{bN_X} \right\}$$

$$\delta\rho(\text{PLT}) = \delta\rho_A(\text{PLT}) \left\{ 1 - a N_R^{3/2} \frac{H_R}{R_O} [\cos E'(\text{REC})]^{bN_X} \right\}$$

(for IDOP = 1 only)

$$a = .27 \times 10^8, \quad b = 1.4 \times 10^6$$

The totality of range corrections (with start and end time superscripts restored) used in the Doppler measurement models of section 3.2 are as follows:

$$\delta\rho^{(s)}(\text{REC}), \delta\rho^{(e)}(\text{REC}), \delta\rho^{(s)}(\text{TXM}), \delta\rho^{(e)}(\text{TXM}), \delta\rho^{(s)}(\text{PLT}), \delta\rho^{(e)}(\text{PLT})$$

3.5.3 Elevation Refraction Correction Model

The elevation refraction correction δE applies directly to A,E angles (sec. 3.3.1). For X,Y angles (sec. 3.3.2 and 3.3.3), the refraction correction are simple functions of δE , and are given in these sections.

Recalling that angle measurements apply only to the receiver leg, the computational requirements are as follows:

a. Compute a empirical factors A,B,C:

$$A = \alpha_0 + \alpha_2 N_R^2$$

$$B = b_0 + b_1 N_R + b_2 N_R^2$$

$$C = c_0 + c_1 N_R + c_2 N_R^2$$

$a_0, a_2, b_0, b_1, b_2, c_0, c_1, c_2$, are system parameters

b. Compute elevation refraction correction:

$$\delta E = \frac{N_R \cos E' [1 + A \exp (-B \sin E')]}{(1-C) [\sin^2 E' + 2 H_R/R_0]^{1/2} + C \sin E'}$$

$$* \left\{ 1 - \frac{R_0}{\rho} [(\sin^2 E' + 2H_R/R_0)^{1/2} - \sin E'] \right\}$$

$$\rho = (\xi^2 + \eta^2 + \zeta^2)^{1/2}$$

3.6 M50 TO ENU-TOPODETTIC TRANSFORMATION

This transformation is used in the OCM angle measurement models and in all of the refraction correction models. The coordinate systems (and transformation) are defined in detail in volume XIV of these requirements. The formal computation procedure is given here.

The inputs required for this transformation (as used by the OCM) are as follows:

- a. $\vec{\rho}, t$ = relative vector (M50 coordinate) and associated time
- b. $(\lambda, r_G, Z_G, \phi_D)$ = geodetic coordinates of origin of the vector $\vec{\rho}$
(ground station coordinates)

λ = longitude east of Greenwich

r_G = distance from Earth spin axis

Z_G = distance above Earth equator

ϕ_D = geodetic latitude

- c. Parameters obtained from system interfaces

ω = Mean sidereal Earth rate

$[RNP]$ = M50 to TEI transformation matrix for time t .

The computational procedure is as follows:

- a. Construct transformation matrix A, which transforms relative vectors from TEI to ENU-topodetic coordinates.

$$[A] = \begin{bmatrix} -\sin(\lambda + \omega t) & \cos(\lambda + \omega t) & 0 \\ -\sin \phi_D \cos(\lambda + \omega t) & -\sin \phi_D \sin(\lambda + \omega t) & \cos \phi_D \\ \cos \phi_D \cos(\lambda + \omega t) & \cos \phi_D \sin(\lambda + \omega t) & \sin \phi_D \end{bmatrix}$$

- b. Compute ENU-topodetic components of $\vec{\rho}$:

$$\begin{bmatrix} \xi \\ \eta \\ \zeta \end{bmatrix} = [A] [RNP] \vec{\rho}$$

4.0 INPUTS TO OCM

The input parameters supplied to the OCM by the user function are listed below.

Parameter	Description
IDOP	Flag that defines tracking configuration 0 = direct tracking ; 1 = relay tracking
EPH(I)	Nine-point ephemeris tables For IDOP = 0; EPH(1) = Target vehicle ephemeris Others blank For IDOP = 1: EPH(1) = TDRS-2 ephemeris EPH(2) = Target vehicle ephemeris EPH(3) = TDRS-1 ephemeris
$(\lambda_R, r_{GR}, z_{GR}, \phi_{DR})$	Receiver location parameters
$(\lambda_X, r_{GX}, z_{GX}, \phi_{DX})$	Transmitter location parameters

Parameter	Description
N_R, H_R	Refraction modulus and atmospheric scale height for receiver
N_X, H_X	Refraction modulus and atmospheric scale height for transmitter
IDT, NR, NX, SNR, ST, REFIN	Flags used for a particular implementation method (appendix A)

 Inputs for range measurement models

t_R	Range measurement time at receiver
G_{RNG}	Range measurement
A_R	Range ambiguity interval (IDOP = 1 only)

 Inputs for Doppler measurement models

t_R	Doppler measurement time (end time of Doppler count interval at receiver)
G_{DOP}	Doppler measurement
τ	Doppler count interval
ν_{NX}	Reference frequency
K	Doppler frequency model multiplier
ω_3	Offset frequency in Doppler extractor
(bF_p)	Return link TDRS translation frequency (return link pilot tone frequency)
b_D	Doppler measurement bias

 Inputs for angle measurement models

t_R	Angle measurement time at receiver
Identifier for angle measurement type	A, E = azimuth and elevation $X_{N/S}, Y_{N/S}$ = angles for N/S antenna mount $X_{E/W}, Y_{E/W}$ = angles for E/W antenna mount

 Inputs for angle measurement models

G_{ANG1}, G_{ANG2} Angle measurements

G_{ANG1} corresponds to azimuth or an X angle

G_{ANG2} corresponds to elevation or a Y angle

5.0 OUTPUTS FROM OCM

The output parameters supplied by the OCM to the user are listed as follows:

Parameter	Description
<hr/> Range measurements <hr/>	
\vec{R}_p, t_p	Position (M50 coordinate) and participation time for each point signal path
	For IDOP = 0 : p = 1,2,3
	For IDOP = 1 : p = 1,2,3,4,5
\vec{V}_Q	Velocity (M50 coordinates) of target vehicle at participation time t_Q
$\Delta t(p)$	Signal delay times for each signal path leg
	For IDOP = 0 : p = 1,2
	For IDOP = 1 : p = 1,2,3,4
S	Computed range measurement (in internal distance units) for receiver measurement time $t_R = t_1$
D(S)	Range residual = Observed value - Computed value

Parameter	Description
<hr/> Range measurements <hr/>	
E(1)	Receiver leg elevation

Parameter	Description
<hr/> Doppler measurements <hr/>	
$\vec{R}_p(s), t_p(s)$	Position (M50 coordinate) and participation time for each point on signal path
$\vec{R}_p(e), t_p(s)$	Superscript (s): start time of count interval Superscript (e): end time of count interval For IDOP = 0 : p = 1,2,3 For IDOP = 1 : p = 1,2,3,4,5,6
$\vec{V}_Q(s), \vec{V}_Q(e)$	Velocity (M50 coordinate) of target vehicle at participation times $t_Q(s)$ and $t_Q(e)$ For IDOP = 0 : Q = 2 For IDOP = 1 : Q = 3
$\Delta t(s)(p), \Delta t(e)(p)$	Signal delay times for each signal path leg corresponding to start and end times of count interval For IDOP = 0 : p = 1,2 For IDOP = 1 : p = 1,2,3,4,5
f	Computed Doppler measurement for receiver measurement time $t_R = t_1(e)$ (Units of f are internal frequency units assumed to be Hz)
D(f)	Doppler Residual: Observed value - Computed value
E(1)	Receiver leg elevation

Parameter	Description
Angle measurements	
\vec{R}_p, t_p	Position (M50 coordinate) and participation time for each point on signal path $p = 1, 2, (\text{IDOP} = 0 \text{ only applies})$
\vec{V}_2	Velocity (M50 coordinate) of target vehicle at participation time t_2
$\Delta t(p)$	Signal delay times for each signal path leg $p = 1 (\text{IDOP} = 0 \text{ only applies})$
$\vec{R}_{T/D} = (\xi, \eta, \zeta)$	Position components (in ENU-topodetic coordinates) of the receiver leg range vector
ρ^2	Square of magnitude of receiver leg range vector
A	Transformation matrix for measurement time $t_R = t_1$ (from TEI to ENU-topodetic)
RNP	Transformation matrix for measurement time $t_R = t_1$ (from M50 to TEI)
A, E	Computed azimuth and elevation angles for receiver measurement time $t_R = t_1$
$X_{N/S}, Y_{N/S}$	Computed X-Y angles (for E/W antenna mount) for receiver measurement time $t_R = t_1$
$X_{E/W}, Y_{E/W}$	Computed X-Y angles (for E/W antenna mount) for receiver measurement time $t_R = t_1$
D(A), D(E)	Angle Residuals = Observed value - Computed value for angle measurement type processed
$D(X_{N/S}), D(Y_{N/S})$	
$D(X_{E/W}), D(Y_{E/W})$	

6.0 CONSTRAINTS

All computations are performed in double precision.

7.0 SUPPLEMENTARY INFORMATION

The observation computation module may be exercised by either the differential correction module (DCM) or the residual computation processor (RCP).

8.0 REFERENCE

1. Level B Software Preliminary Orbit Determination Processing Formulation Requirements. JSC IN 77-FM-57, October 1977.

9.0 BIBLIOGRAPHY

1. Proposed Light Time Algorithm. TRW 78:2511.4-03, January 1978.
2. Relayed Range and Doppler Measurement Model Computations. TRW 78:2511.4-13, May 4, 1978.
3. Shuttle Mission Control Center External Communications Interface Control Document, Volume 1, JSC/GSFC Operational Communications Interface Control Document for Shuttle Orbital Flight Test. JSC-11534, January 23, 1978.
4. SSA TDRSS Range and Doppler Data, TRW 78:2511.4-49, November 22, 1978.
5. High-Precision Refraction Correction Algorithms. JSC IN 78-FM-44, August 1978.

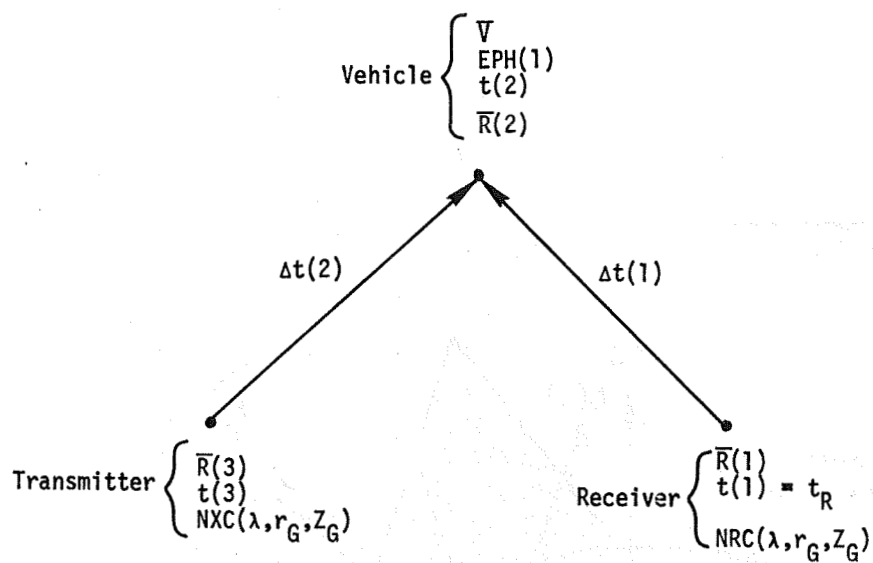


Figure 1.- Direct data signal path configuration.

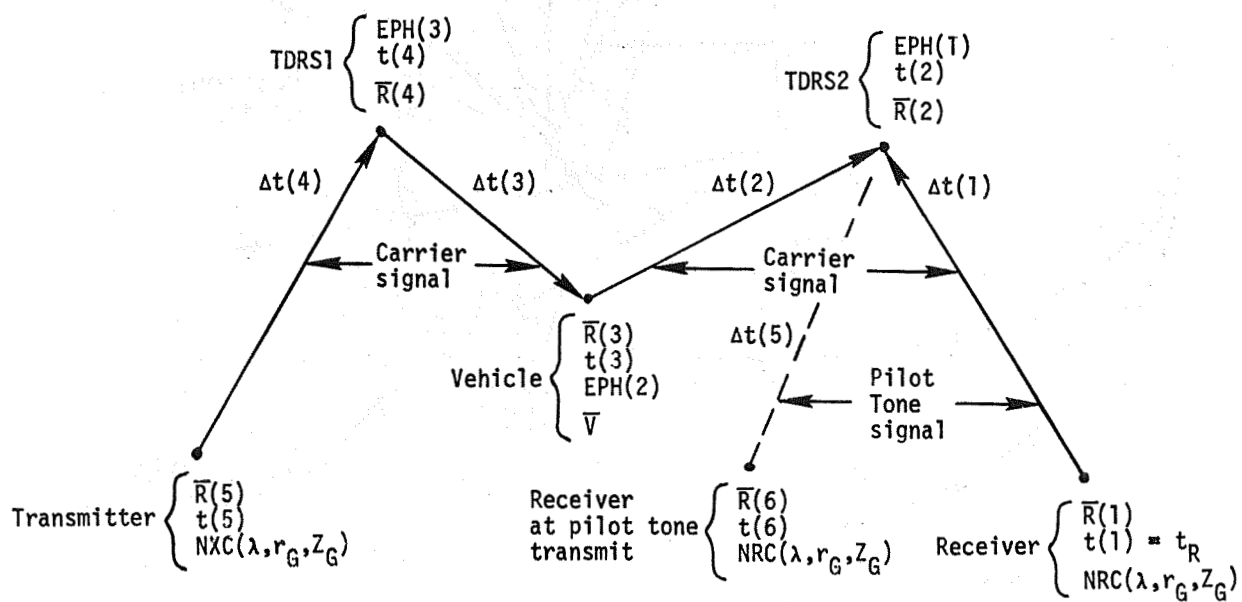


Figure 2.- Relayed data signal path configuration.

$$A = \text{TAN}^{-1} (\xi/n)$$

$$E = \text{TAN}^{-1} [\xi / \sqrt{(\xi)^2 + (n)^2}]$$

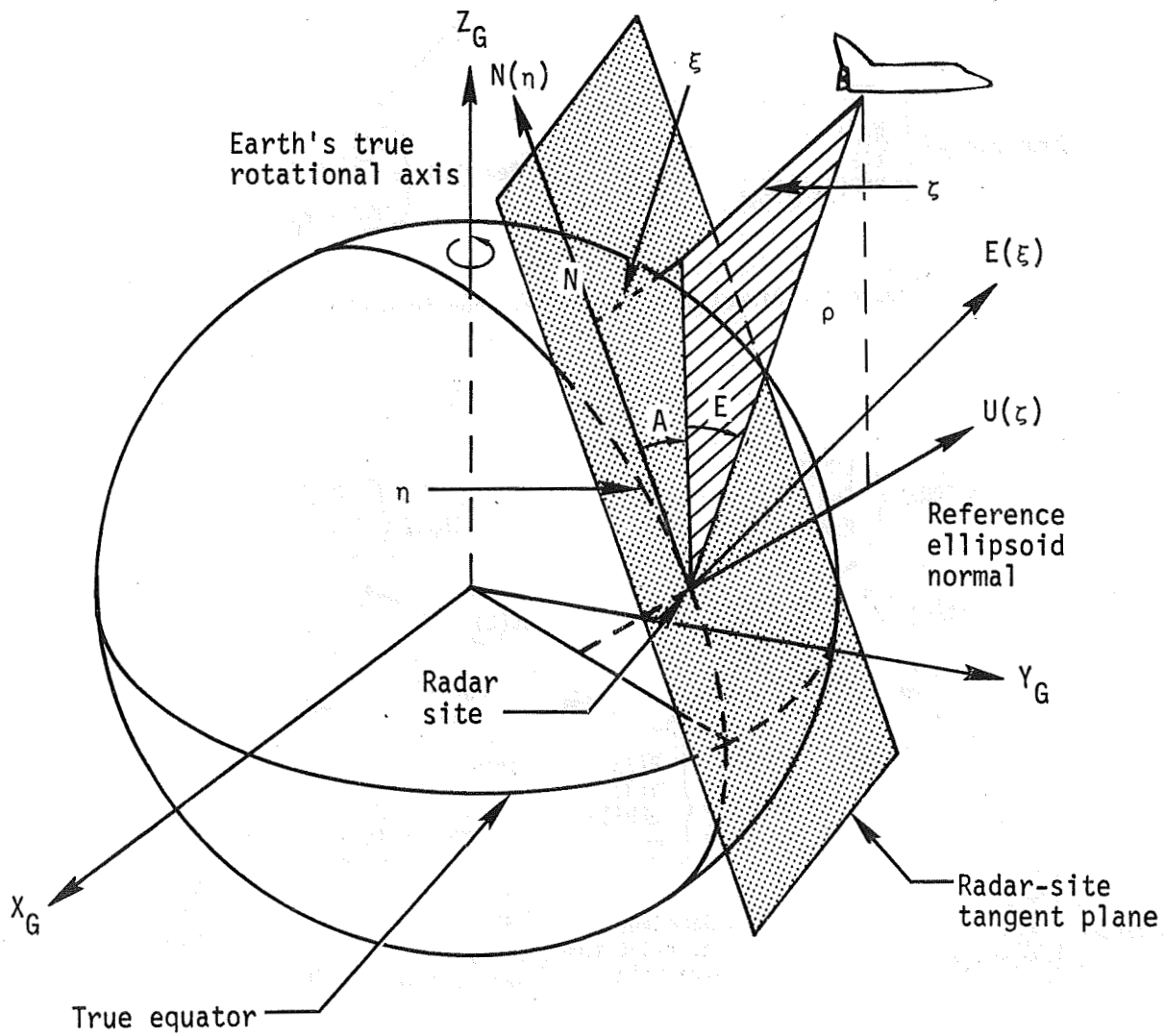
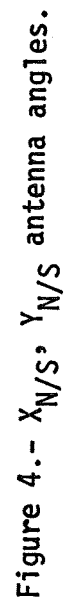


Figure 3.- Azimuth, elevation angles.

$$\begin{aligned} X_{N/S} &= \text{TAN}^{-1} \left[\frac{\xi}{\zeta} \right] \\ Y_{N/S} &= \text{TAN}^{-1} \left[\frac{\eta}{(\xi^2 + \zeta^2)^{1/2}} \right] \\ X_{N/S}, Y_{N/S} &= [0, \pi/2] \text{ or } [3\pi/2, 2\pi] \end{aligned}$$

$$Y_{N/S} = \tan^{-1} \left[\frac{\eta}{(\xi^2 + \zeta^2)^{1/2}} \right]$$

$$x_{N/S}, y_{N/S} \in [0, \pi/2] \text{ or } [3\pi/2, 2\pi]$$



$$X_{E/W} = \text{TAN}^{-1} \left[\frac{-\eta}{\zeta} \right]$$

$$Y_{E/W} = \text{TAN}^{-1} \left[\frac{\xi}{(\eta^2 + \zeta^2)^{1/2}} \right]$$

$$X_{E/W}, Y_{E/W} \in [0, \pi/2] \text{ or } [3\pi/2, 2\pi]$$

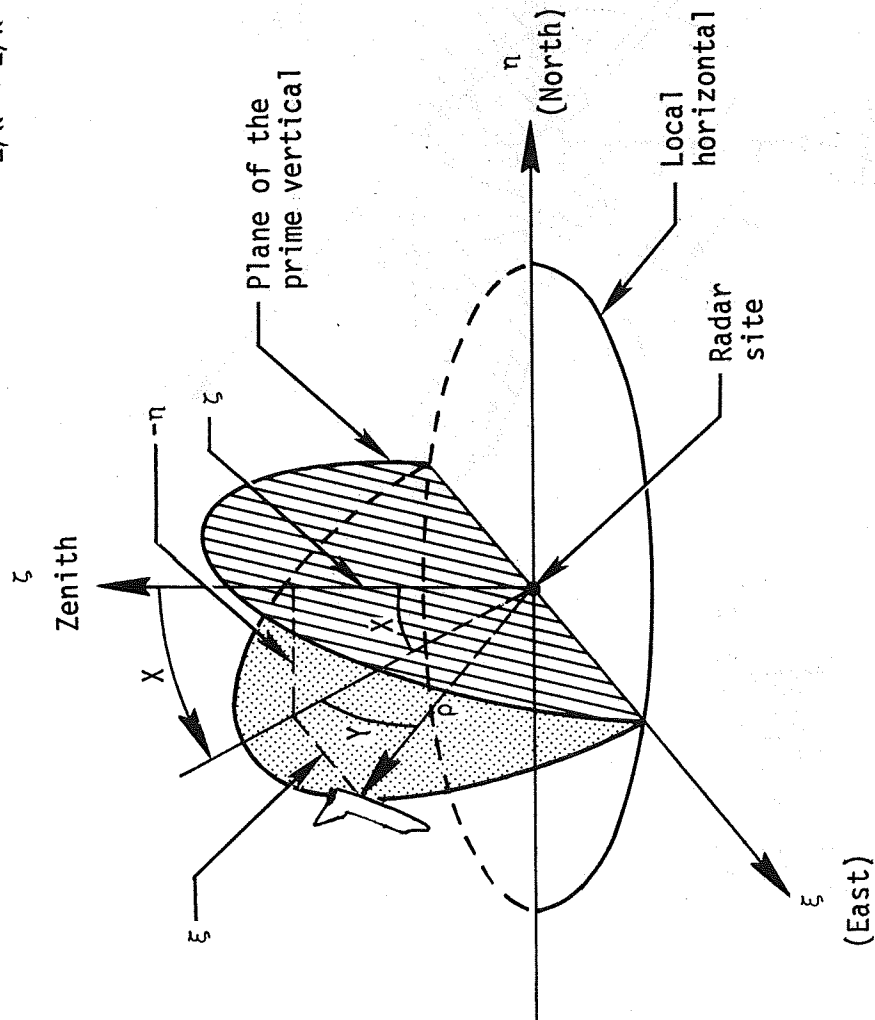


Figure 5.- $X_{E/W}$, $Y_{E/W}$ antenna angles.

APPENDIX A

FLOW CHARTS FOR OCM MECHANIZATION

The flow charts contained in this appendix present a particular mechanization of the functional requirements given in the text. They are included only as an aid to assist in the understanding of the functional requirements. There is no implication that the mechanization shown is the most efficient for the real time program,

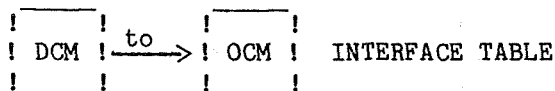
Partial List of Symbols

The symbols used in the flow charts are generally the same as those used in the text. The exceptions are noted in the following list.

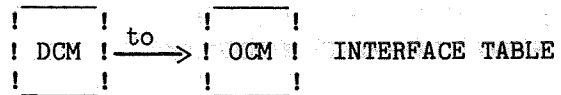
<u>Parameter</u>	<u>Definition</u>
IDT	Flag that specifies data type
=1	Azimuth angle
2	Elevation angle
3	$X_{N/S}$ angle
4	$Y_{N/S}$ angle
5	$X_{E/W}$ angle
6	$Y_{E/W}$ angle
7	Range
8	Doppler
X_{TD}, Y_{TD}, Z_{TD}	ENU topodetic coordinates (ξ, η, ζ) is used in the test
NRC	Indicates the set of receiver parameters: $\lambda_R, r_{GR}, Z_{GR}, \phi_{DR}, N_R, H_R$
NXC	Indicates the set of transmitter parameters: $\lambda_X, r_{GX}, Z_{GX}, \phi_{DX}, N_X, H_X$
$\Delta\rho, \Delta E$	Refraction corrections ($\delta\rho, \delta E$ used in text)

<u>Parameter</u>	<u>Definition</u>
$\vec{R}_{V/S}$	M50 station to vehicle relative vector ($\vec{\rho}$ is used in the text)
NR	Receiver ID
NX	Transmitter ID
SNR	Receiver ID from previous call
ST	Measurement time from previous call
n	n = 5 for IDOP = 1 ; n = 3 for IDOP = 0

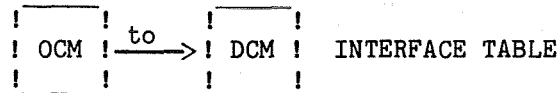
Interface table for the OCM are also contained in this appendix.



DCM parameter	OCM parameter	Unit	Description
(Vol. VII, table VI)	(Sec. no.)		
IDOP	IDOP (3.1,2,3)	Flag	1 = relay 0 = direct
EPH(I)	EPH(I) (3.4)	Int	Nine-point ephemeris tables
Xλ	λX	Int	Transmitter location parameter
Xr _g	rGX		
XZ _G	ZGX		
Xφ _D	φDX		
rλ	λr	Int	Receiver location parameter
rr _G	rGR (3.4.5)		
XN _O	N _x	Int	Transmitter refr. modulus and scale height
XH _S	H _x (3.5)		
rN _C	N _R	Int	Receiver refr. modulus and scale height
rH _S	H _R (3.5)		
t _R	t _R (3.1,2,3)	Int	Measurement time at receiver
G	GRNG	Int	Measurement value
	GDOP (3.1,2,3)	Hz	
	GANG1	Int	
	GANG2	Int	
AR	A _R (3.1)	Int	Range ambiguity interval
τ	τ (3.2)	Int	Doppler count interval
v(NR)	v _{NX} (3.2)	Hz	Reference frequency
K	K (3.2)	Int	Frequency multiplier
ω ₃	ω ₃ (3.2)	Hz	Offset frequency in Doppler extractor

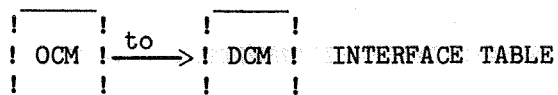


DCM parameter	OCM parameter	Unit	Description
(Vol. VII, table VI)	(Sec. no.)		
BD	b _D (3.2)	Hz	Relay Doppler bias (solve-for)
BF _p	(bF _p) (3.2)	Hz	Return link TDRS translation frequency
IDT	IDT	Flag	Measurement type I.D.
NR	NR	Flag	Current receiver I.D.
NX	NX	Flag	Current transmitter I.D.
SNR	SNR	Flag	Receiver ID from previous call
ST	ST	Int	Measurement time from previous

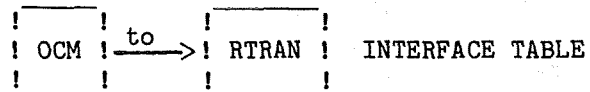


INTERFACE TABLE

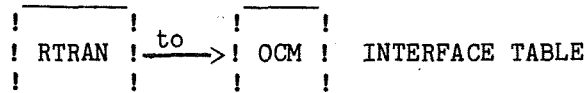
OCM parameter	DCM parameter	Unit	Description
(Sec. no.)	(Sec. no.)		
$\vec{R}_p^{(e)}, t_p^{(e)}$	$\vec{R}(p), t(p)$	Int	M50 position and epoch of participation of each point on signal path (corresponding to measurement time, t_R)
$\vec{V}_Q^{(e)}(3.1,2,3)$	\vec{V} (App.A)	Int	Vehicle velocity (M50) at vehicle participation
$\vec{R}_p^{(s)}, t_p^{(s)}$	$\vec{R}(p), t(p)$	Int	M50 position and epoch of participation of each point on signal path (corresponding to start time of Doppler count interval, at receiver $t_1^{(s)} = t_R - \tau$)
$\vec{V}_Q^{(s)}(3.2)$	\vec{V} (App.A)	Int	Vehicle velocity (M50) at vehicle participation
$\Delta t_p^{(e)}(3.1,2,3)$	$\Delta t(p)$ (App.A)	Int	Signal delay times for each (p^{th}) signal-path leg (corresponding to measurement time, t_R)
$\Delta t_p^{(s)}(3.2)$	$\Delta t(p)$ (App.A)	Int	Signal delay times for each (p^{th}) signal-path leg (corresponding to start time of Doppler count interval)
$E(1)(3.5)$	$E(I)$ (App.A)	Int	Elevation angle for ground legs
$S(3.1)$	$G(3)$	Int	Computed range measurement



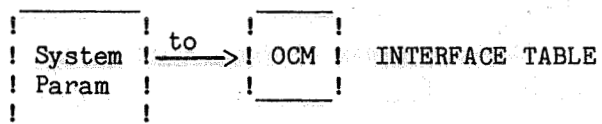
OCM parameter	DCM parameter	Unit	Description
(Sec. no.)	(Sec. no.)		
f (3.2)	G(4)	Hz	Computed Doppler measurement
A, E (3.3)	G(1), G(2)	Int	Computed angle measurement
X _{N/S} , Y _{N/S} (3.3)	G(1), G(2)	Int	Computed angle measurement
X _{E/W} , Y _{E/W} (3.3)	G(1), G(2) (App.A)	Int	Computed angle measurement
D(s) (3.1)	r (App.A)	Int	Measurement residuals (observed-computed)
D(f) (3.2)			
D(A), D(E)			
D(X _{N/S}), D(Y _{N/S})			
D(X _{E/W}), D(Y _{E/W}) (3.3)			
$\vec{R}_{T/D} = (\xi, \eta, \zeta)$ (3.3)	$\vec{R}_{TD}(1)$ (App.A)	Int	Receiver leg range vector in ENU-topodetic coordinate (for angle measurements)
ρ^2 (3.3)	ρ^2 (App.A)	Int	Square of magnitude of receiver leg range vector (for angle measurements)
[A] (3.3)	A (App.A)	Int	Transformation matrix: From TEI to ENU (for angle measurements)
[RNP] (3.3)	RNP (App.A)	Int	Transformation matrix: From M50 to TEI (for angle measurements)



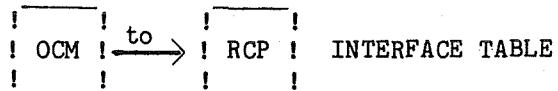
OCM parameter	RTRAN parameter	Unit	Description
(Sec. no.)	(Sec. no.)		
t (3,4,5,6)		Int	Time for which [RNP] is desired



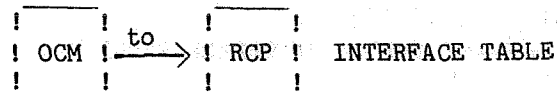
RTRAN parameter	OCM parameter	Unit	Description
(Sec. no)	(Sec. no)		
	[RNP] (3,4,5,6)	Int	RNP-matrix for desired time



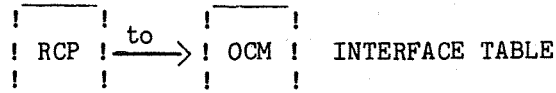
System parameter	OCM parameter	Unit	Description
(Sec. no)	(Sec. no)		
	C (3.1,2,3)	Int	Speed of light
	W (3.4,5,6)	Int	Earth rate (mean sidereal)



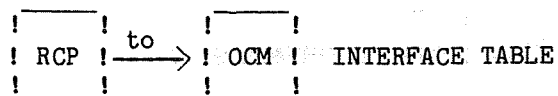
OCM parameter	RCP parameter	Unit	Description
(Sec. no.)	(Sec. no.)		
f (3.2)	N/A	Hz	Computed Doppler measurement
A, E (3.3)	N/A	Int	Computed angle measurement
X _{N/S} , Y _{N/S} (3.3)	N/A	Int	Computed angle measurement
X _{E/W} , Y _{E/W} (3.3)	N/A	Int	Computed angle measurement
D(s) (3.1)	R	Int	Measurement residuals (observed-computed)
D(f) (3.2)	R		
D(A), D(E)	R		
D(X _{N/S}), D(Y _{N/S})	R		
D(X _{E/W}), D(Y _{E/W}) (3.3)	R		
$\vec{R}_{T/D} = (\xi, \eta, \zeta)$ (3.3)	N/A	Int	Receiver leg range vector in ENU-topodetic coordinate (for angle measurements)
ρ^2 (3.3)	N/A	Int	Square of magnitude of receiver leg range vector (for angle measurements)
[A] (3.3)	N/A	Int	Transformation matrix: From TEI to ENU (for angle measurements)
[RNP] (3.3)	N/A	Int	Transformation matrix: From M50 to TEI (for angle measurements)



OCM parameter	RCP parameter	Unit	Description
(Sec. no.)	(Sec. no.)		
$\vec{R}_p^{(e)}, t_p^{(e)}$	\vec{R}	Int	M50 position and epoch of participation of each point on signal path (corresponding to measurement time, t_R)
$\vec{V}_Q^{(e)}(3.1,2,3)$	N/A	Int	Vehicle velocity (M50) at vehicle participation
$\vec{R}_p^{(s)}, t_p^{(s)}$	\vec{R}	Int	M50 position and epoch of participation of each point on signal path (corresponding to start time of Doppler count interval, at receiver $t_1^{(s)} = t_R - \tau$)
$\vec{V}_Q^{(s)}(3.2)$	N/A	Int	Vehicle velocity (M50) at vehicle participation
$\Delta t_p^{(e)}(3.1,2,3)$	N/A	Int	Signal delay times for each (p^{th}) signal-path leg (corresponding to measurement time, t_R)
$\Delta t_p^{(s)}(3.2)$	N/A	Int	Signal delay times for each (p^{th}) signal-path leg (corresponding to start time of Doppler count interval)
$E(1)(3.5)$	E_R, E_X	Int	Elevation angle for ground legs
$S(3.1)$	N/A	Int	Computed range measurement



RCP parameter	OCM parameter	Unit	Description
(Sec. no.)	(Sec. no.)		
IDOP (3.1)	IDOP (3.1,2,3)	Flag	1 = relay 0 = direct
EPH(I) (3.1)	EPH(I) (3.4)	Int	Nine-point ephemeris tables
SCT (3.1)	λ_X r_{GX} Z_{GX} ϕ_{DX}	Int	Transmitter location parameter
SCT (3.1)			
SCT (3.1)			
SCT (3.1)			
SCT (3.1)	λ_r r_{GR} (3.4.5)	Int	Receiver location parameter
SCT (3.1)			
SCT (3.1)	N_X	Int	Transmitter refr. modulus and scale height
SCT (3.1)	H_X (3.5)		
SCT (3.1)	N_R	Int	Receiver refr. modulus and scale height
SCT (3.1)	H_R (3.5)		
T_R (3.1.1)	t_R (3.1,2,3)	Int	Measurement time at receiver
G (3.1.1)	GRNG	Int	Measurement value
G (3.1.1)	GDOP (3.1,2,3)	Hz	
G (3.1.1)	GANG1	Int	
G (3.1.1)	GANG2	Int	
A_R (3.1.1)	A_R (3.1)	Int	Range ambiguity interval
τ (3.1.1)	τ (3.2)	Int	Doppler count interval
ν_{NX} (3.1.1)	ν_{NX} (3.2)	Hz	Reference frequency
K (3.1.1)	K (3.2)	Int	Frequency multiplier
ω_3 (3.1.1)	ω_3 (3.2)	Hz	Offset frequency in Doppler extractor



RCP parameter	OCM parameter	Unit	Description
(Sec. no.)	(Sec. no.)		
b _D (3.1)	b _D (3.2)	Hz	Relay Doppler bias (solve-for)
bF _p (3.1.1)	(bF _p) (3.2)	Hz	Return link TDRS translation frequency
	IDT	Flag	Measurement type I.D.
	NR	Flag	Current receiver I.D.
	NX (App. A)	Flag	Current transmitter I.D.
	SNR	Flag	Receiver ID from previous call
	ST	Int	Measurement time from previous

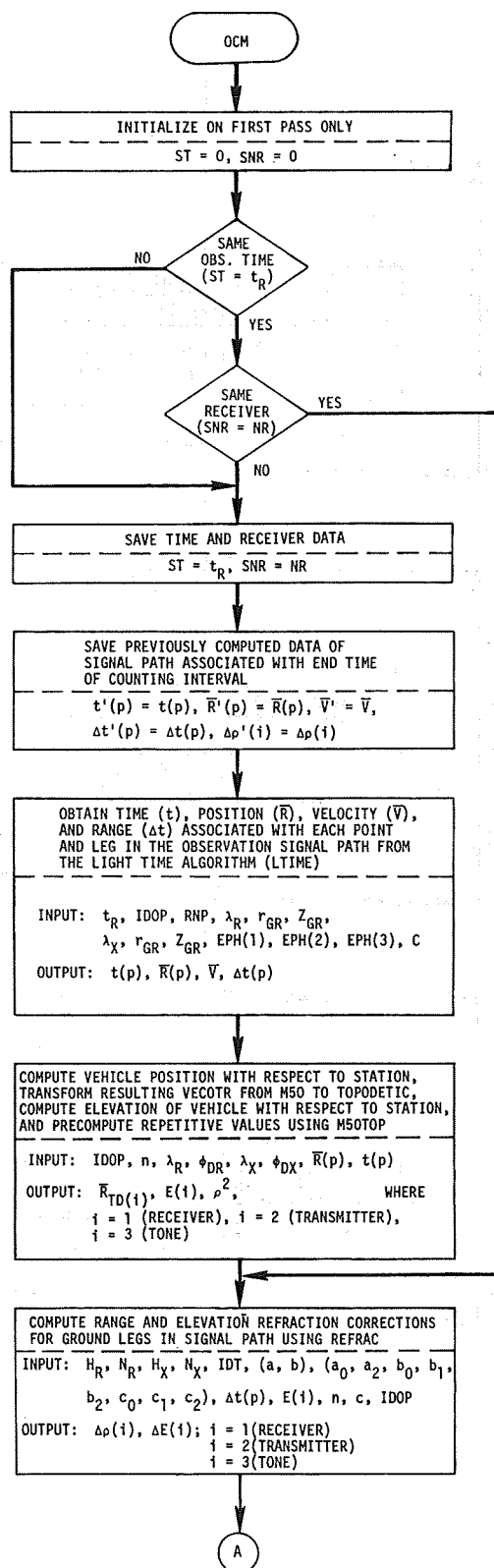


Figure A-1.- Observation Computation Module (OCM) flow diagram.

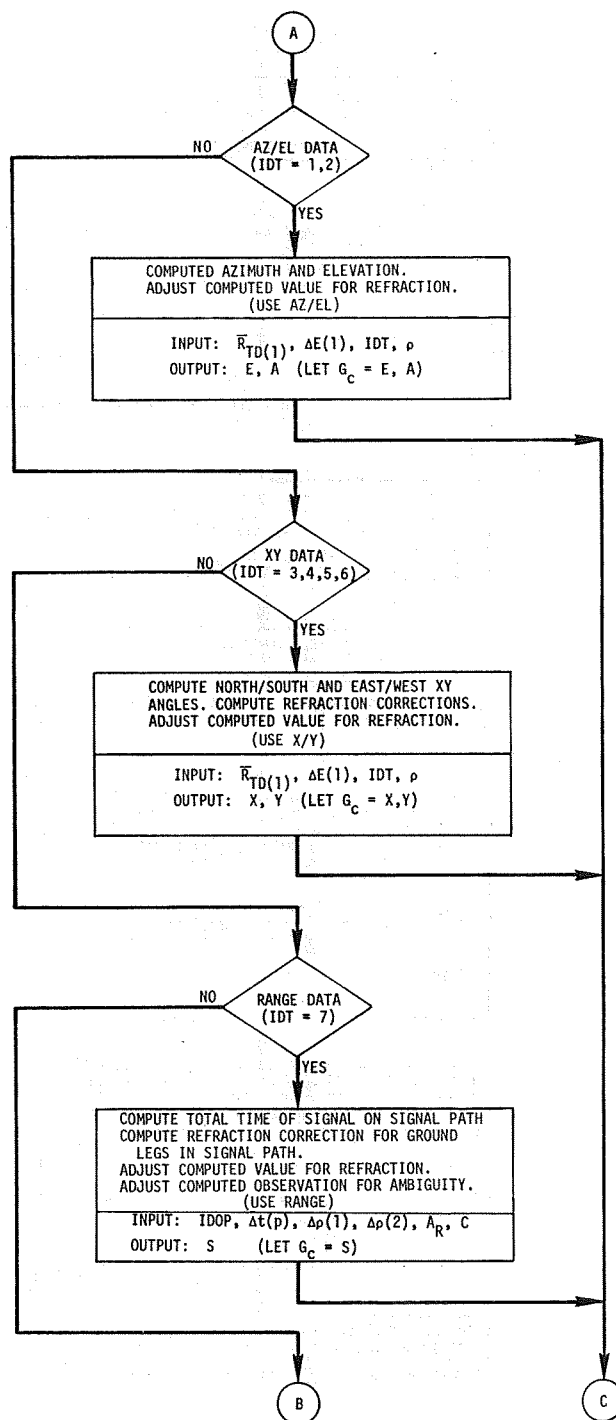


Figure A-1.- Continued.

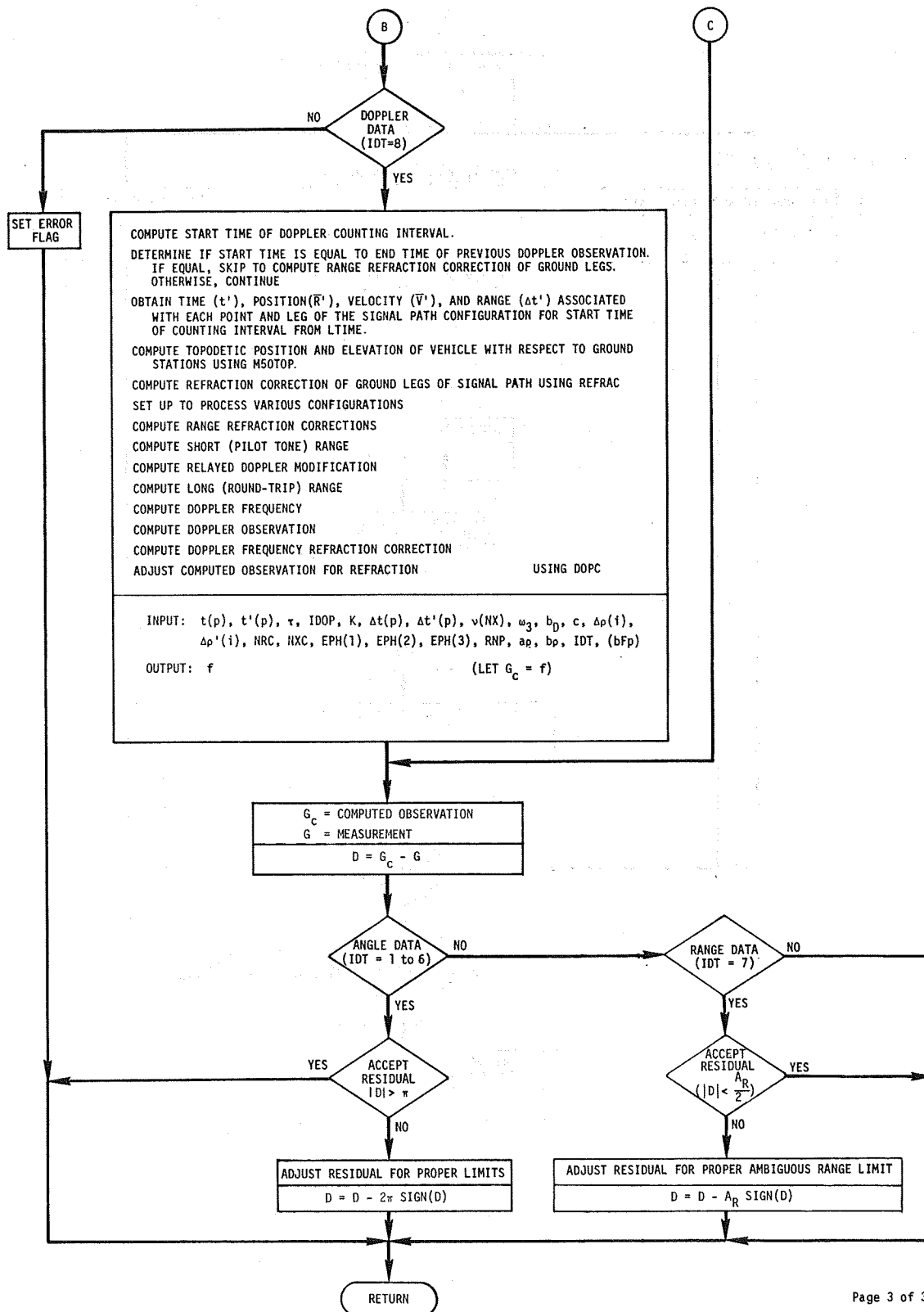


Figure A-1.- Concluded.

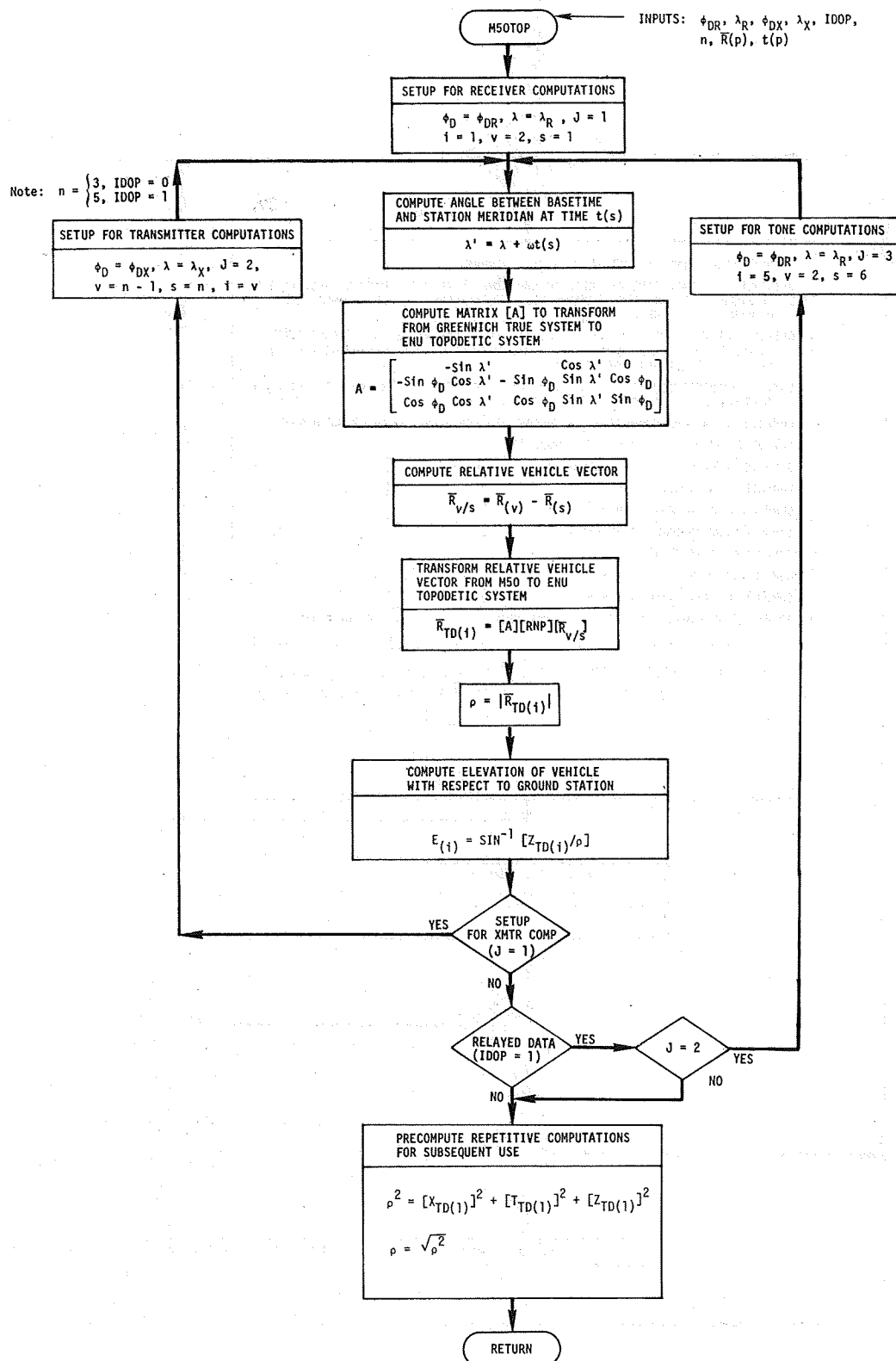


Figure A-2.- Mean of 1950 to ENU topodetic (M50TOP) transformation flow diagram.

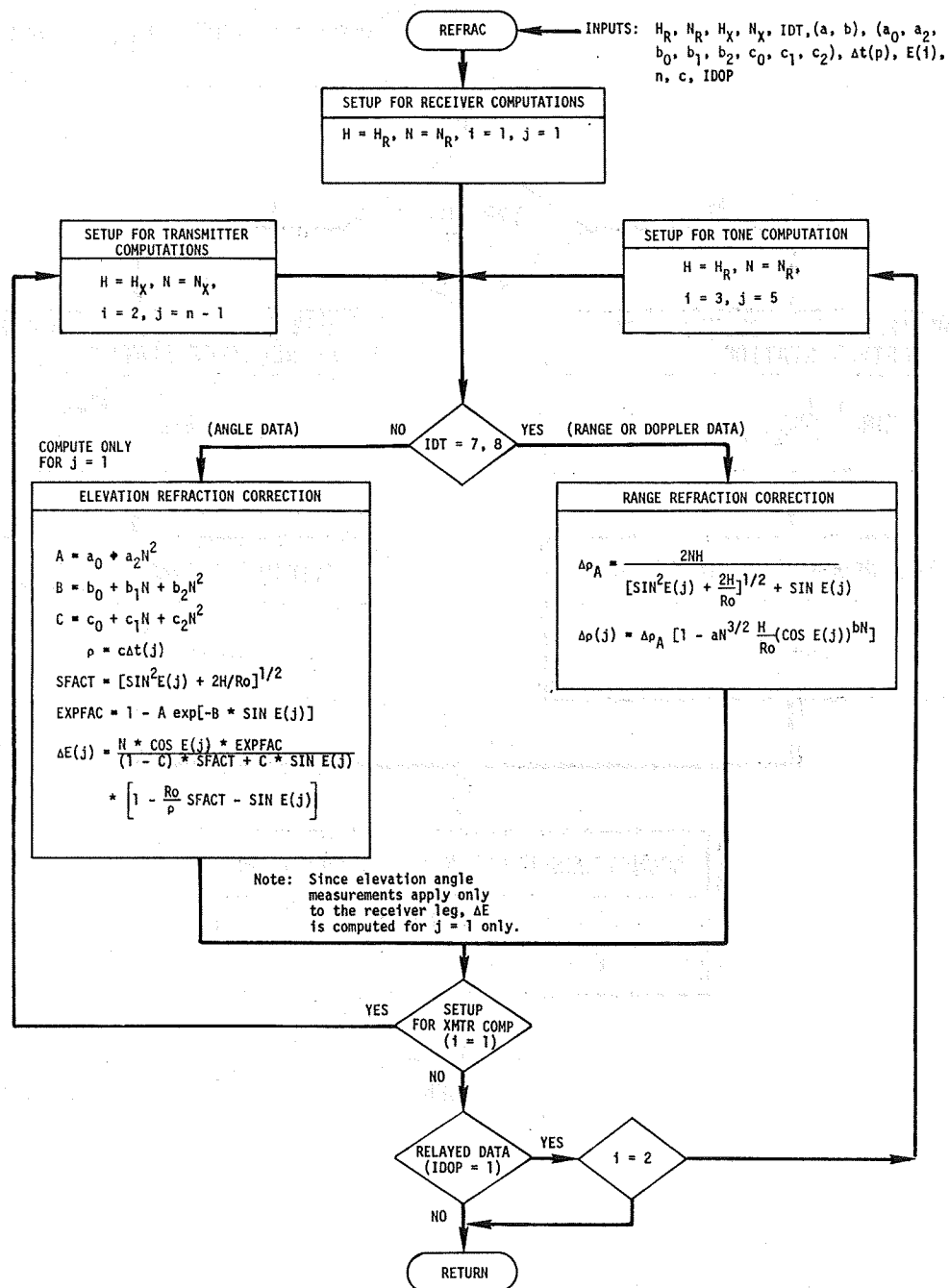


Figure A-3.- Refraction (REFRAC) computation flow diagram.

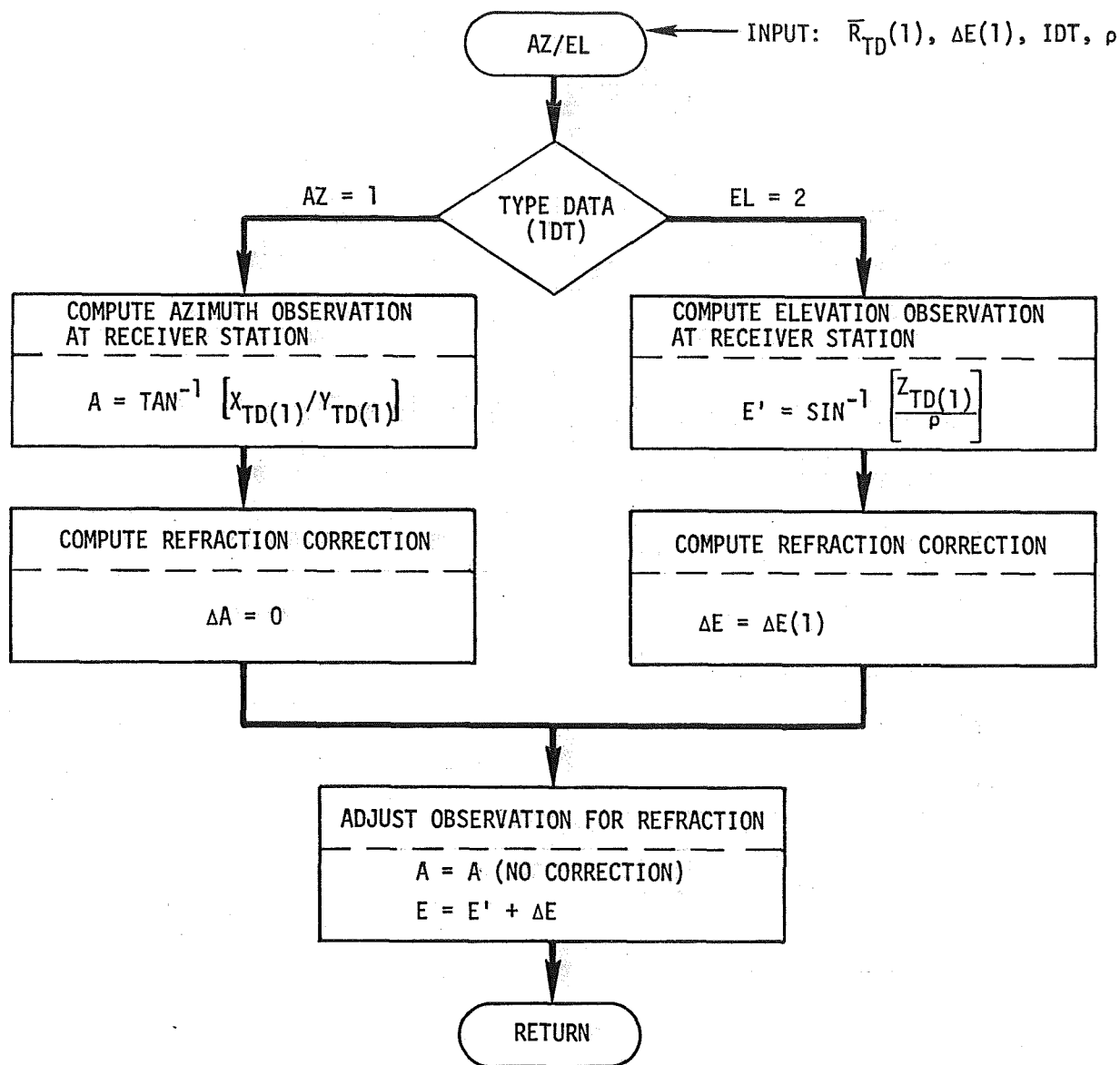


Figure A-4.- Azimuth/elevation (AZ/EL) computation flow diagram.

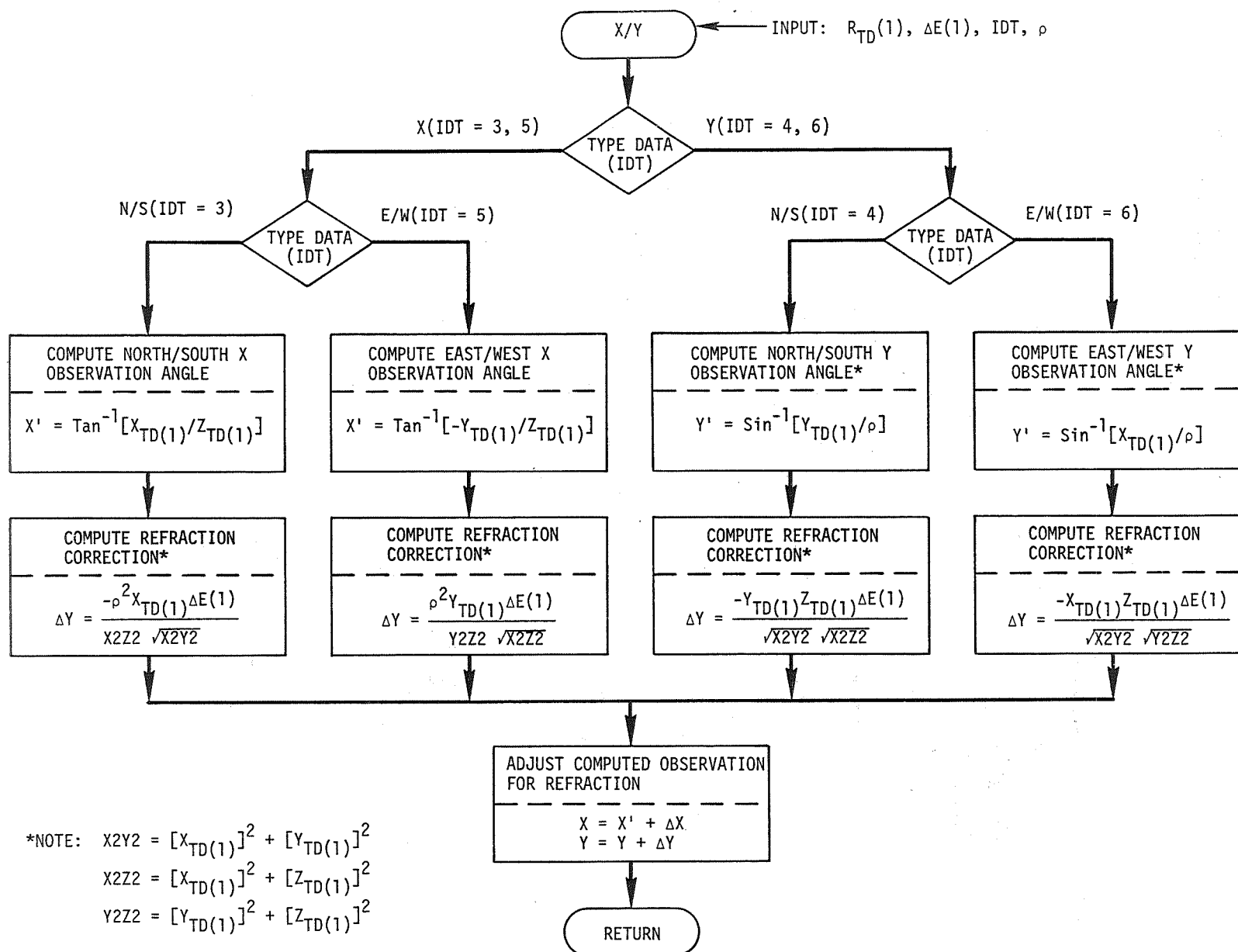


Figure A-5.- X and Y (X/Y) angle computation flow diagram.

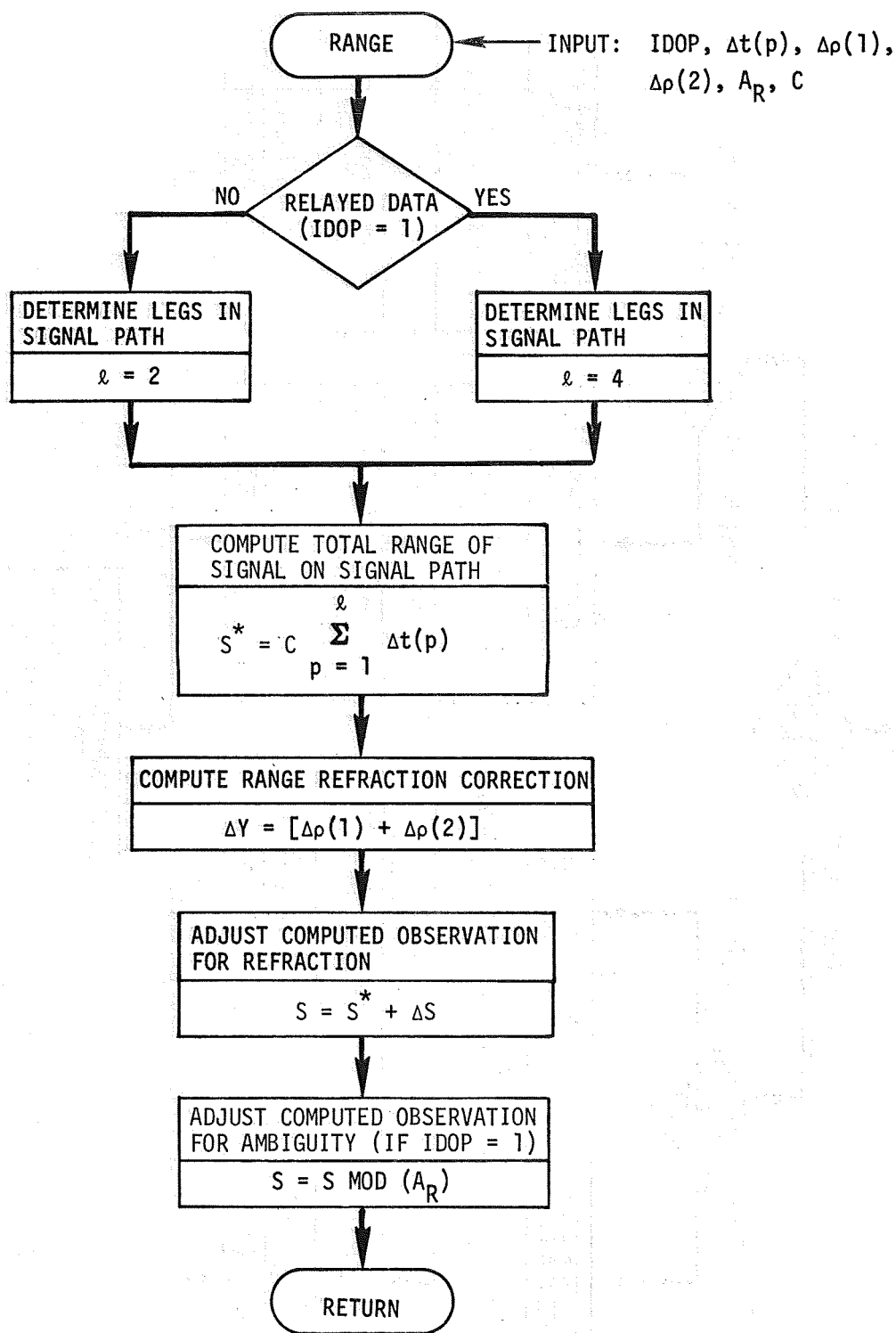


Figure A-6.- Range computation flow diagram.

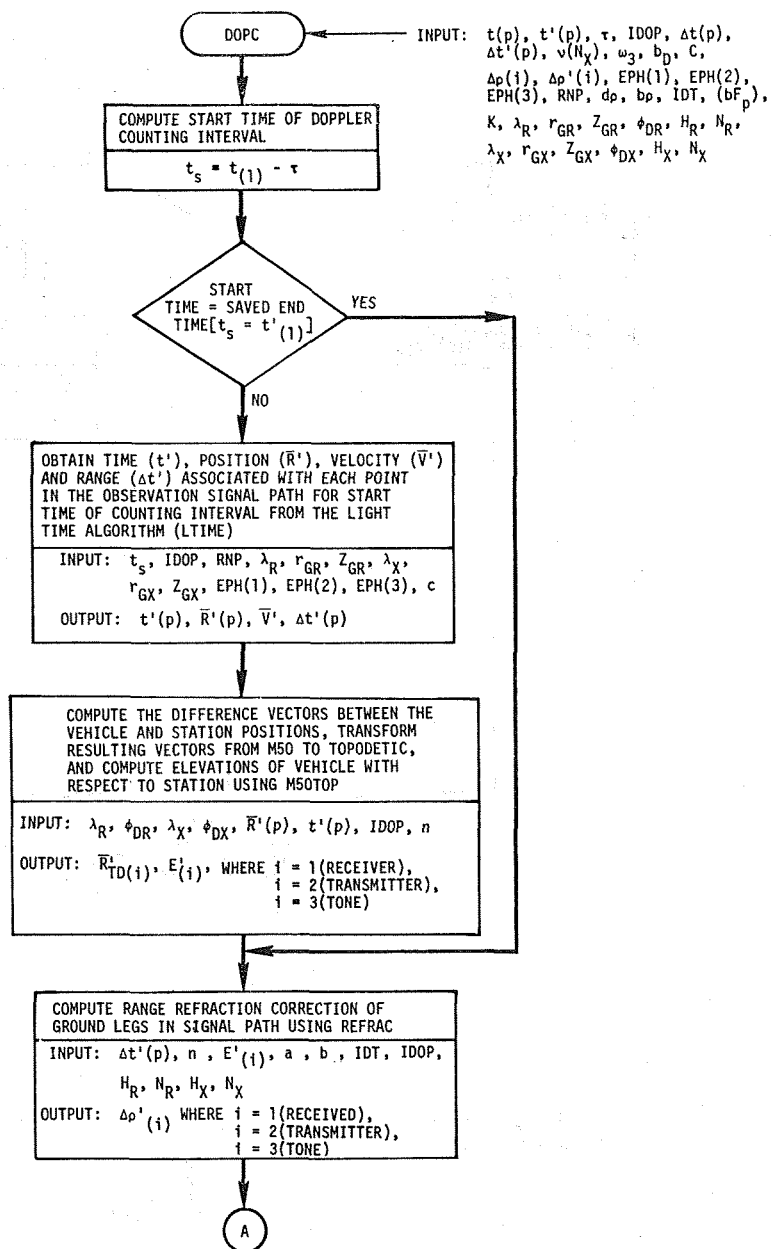


Figure A-7.- DOPPLER computation (DOPC) flow diagram.

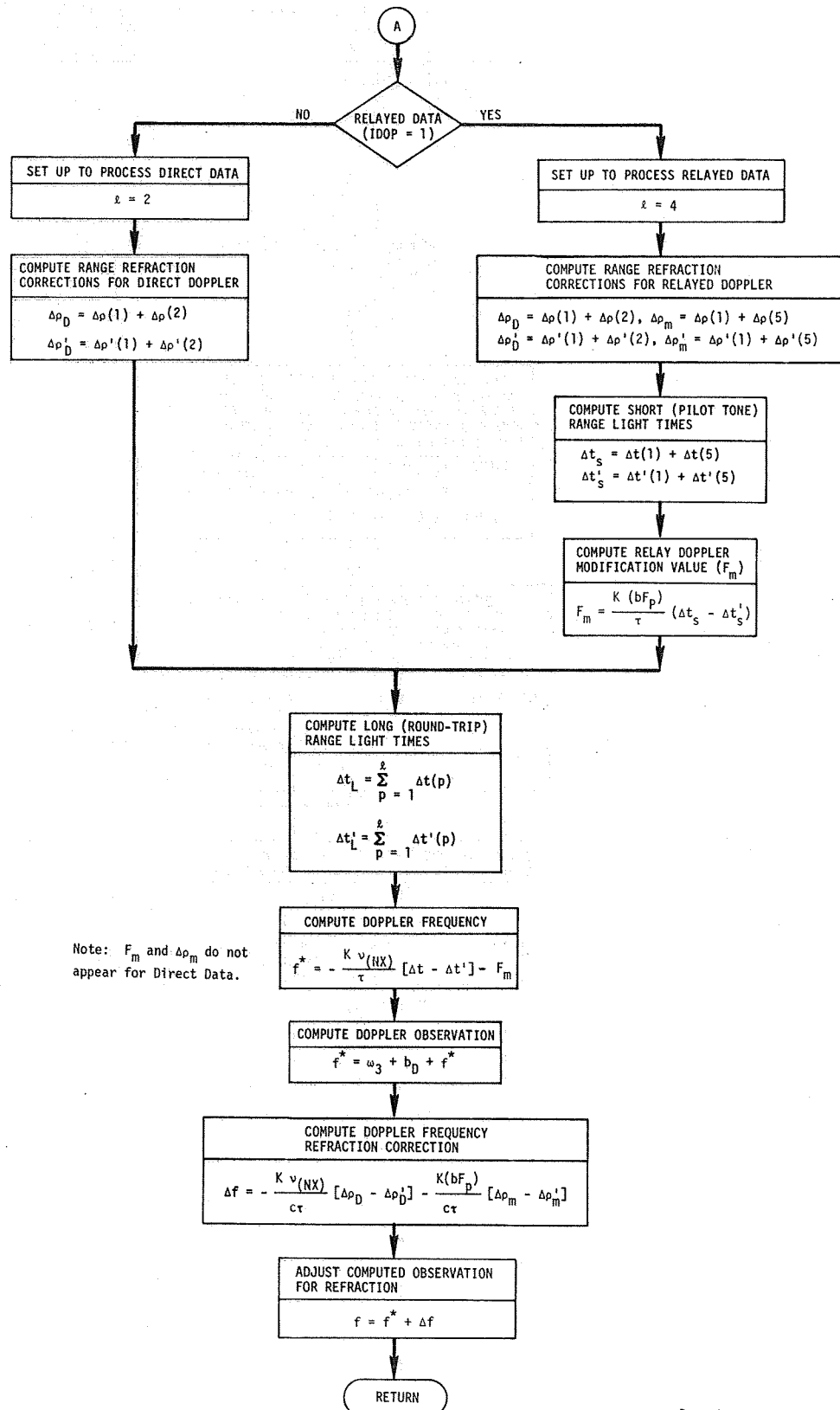


Figure A-7.- Concluded.

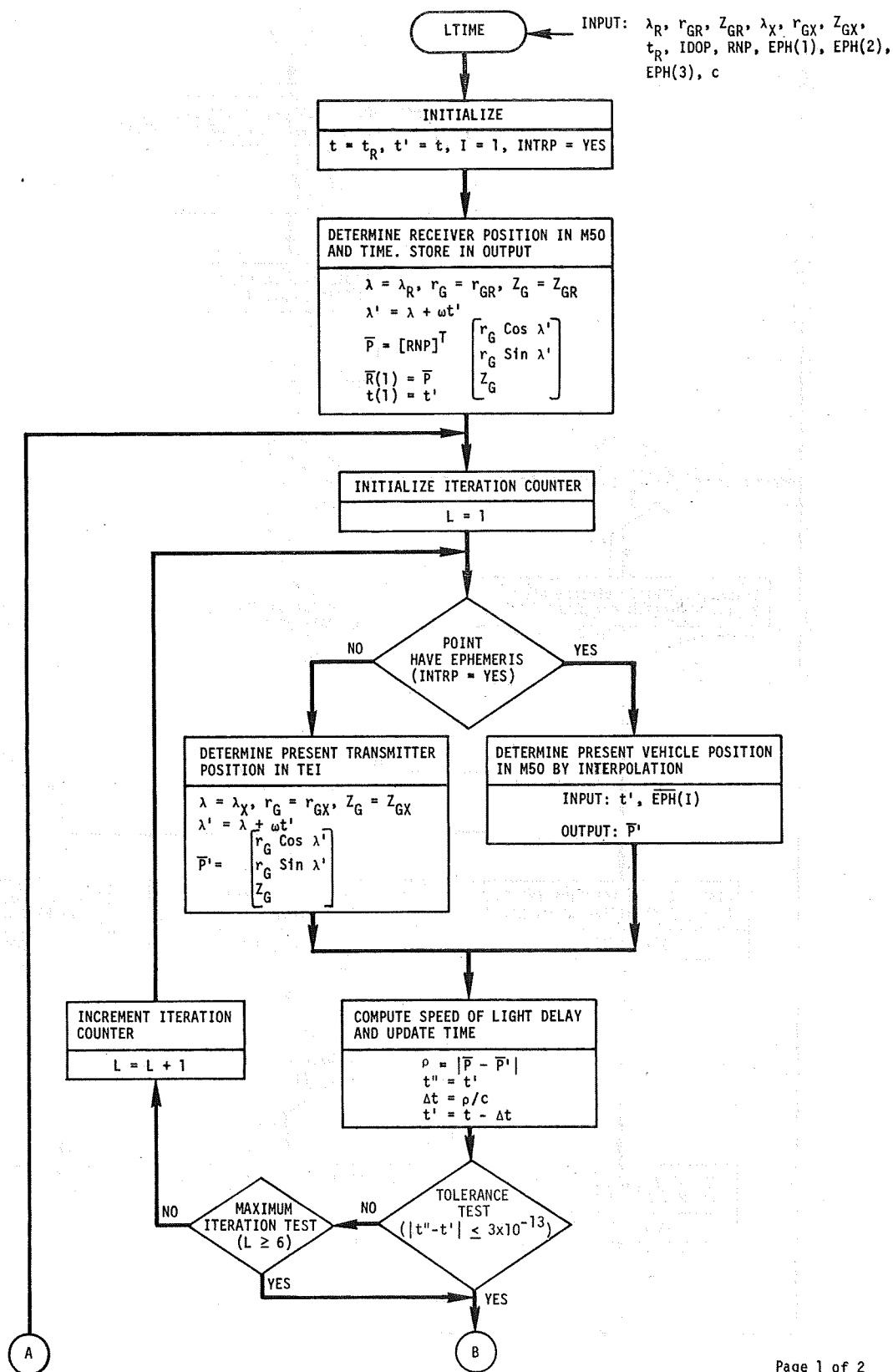
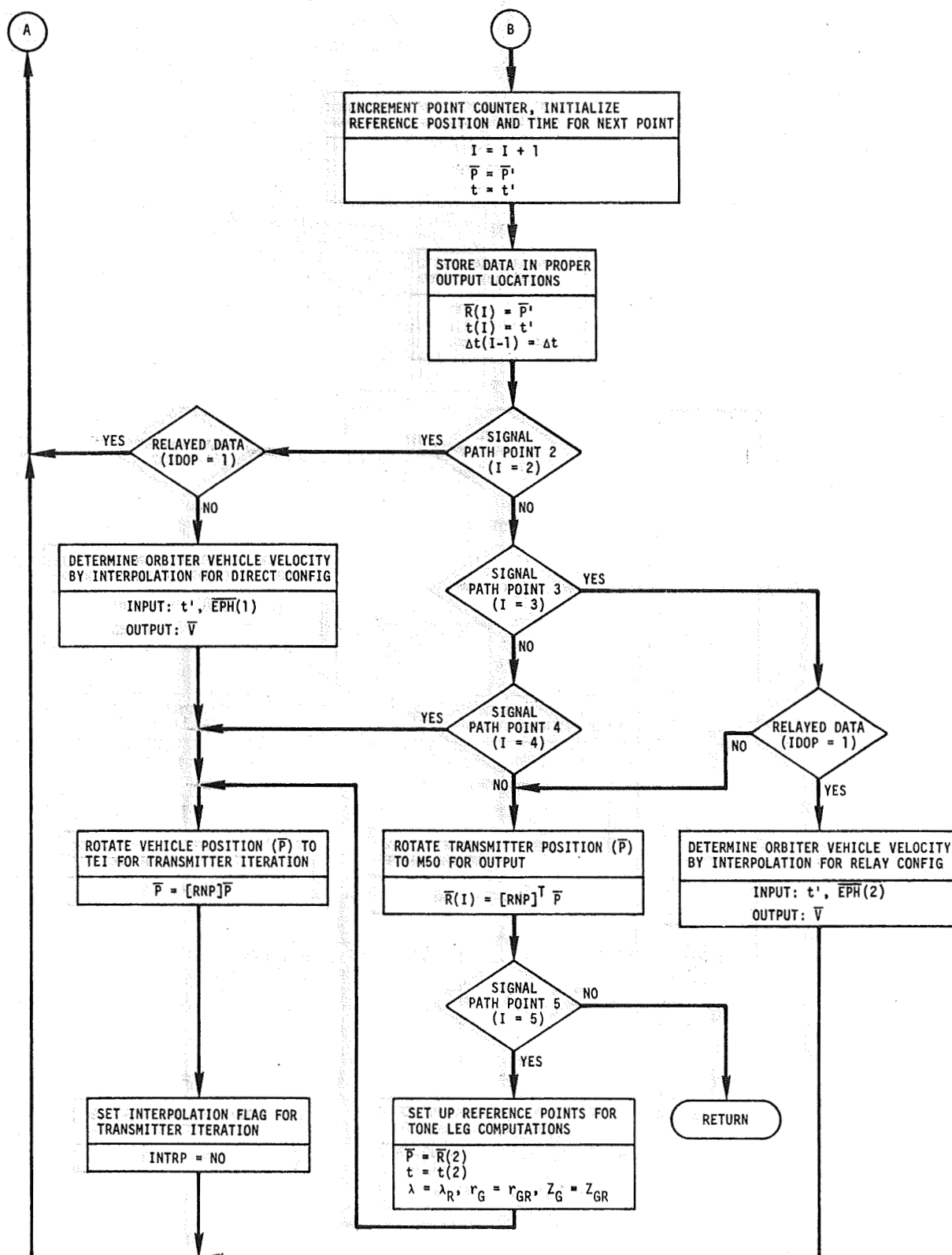


Figure A-8.- Light time (LTIME) algorithm flow diagram.



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